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Research document

AGRO-CYCLE PROJECT

Centre of Expertise - Energy

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SUMMARY

The 'AgroCycle' project investigates whether a cooperation of farms can become self-sufficient in energy and fertilization by using manure and organic waste streams for the production of energy, green fuel and green fertilizers by means of anaerobic digestion (AD). In the project, the project partners aim to link the nutrient cycle (from manure to digestate to green fertilizer) to a self-sufficient energy system (biomass to biogas to green fuel for processing the land) through the combined production of biogas and green fertilizers. The financial feasibility of a bio-digester is highly dependent on the use and economic value of the digestate. This combined approach increases both feasibility and sustainability (environmental impacts and CO2 emissions). To explore the feasibility of the aforementioned concept, use is made of the existing 'BioGas simulator' model developed by Hanze UAS to simulate the technical process of decentralized production of biogas and the economic cost.

The project has shown that there is a clear environmental benefit in applying a circular AD system within a cooperation of farmers. From a technical perspective, a circular AD installation is possible, using the currently available technologies. In theory, the system can fill (for a large part) the demand for electricity, gas, fuel and fertilizer for a cooperative of agricultural farmers and livestock farms. Operating a circular cooperative AD system makes it possible to reduce the energy requirement, emissions and environmental impact linked to energy and fertilizer use by around 70%. Interviewed farmers indicated that they find the concept interesting. According to farmers, the balance between organic material present on the land and / or using the same material for producing energy is an important dilemma. Every farmer makes his own considerations within this dilemma. The depletion of the soil is possible to a certain extent, e.g. for the benefit the farmers own energy needs. However, the focus on maximum energy production, in which all the organic material is extracted from the land, can exhaust the soil in such a way that the soil quality is jeopardized. Therefore, finding this balance in biomass use is of great importance in the success of the concept under consideration in this report, because organic material is the fuel of the entire system. Additionally, the quality of the biomass waste products and subsequent digestate must be guaranteed before use as green fertilizer.

Through the use of a stakeholder analysis the interests of the parties where investigated and from this, a business model was constructed. The synergy between agricultural farmers and livestock farmers can be increased by working on a cooperative basis. In the current situation, there is a negotiation between two parties, each with its own interest, while a common goal can be pursued. How farmers can be facilitated in their cooperation is an important follow-up question. Economically, there is potential in the system and there is potential for gaining profit for all stakeholders within the cooperative. However, the current business case is weak due to uncertainties in the continuity of subsidies, but also in the legal status of green fertilizer. In the current EU policy, the use of green fertilizer to replace fossil fertilizer is forbidden. Overall, the balanced integration of energy generation in the shape of AD biogas production within the agricultural sector requires more research, looking at the environment, law and regulations, and the business case.

PROJECT ORGANIZATION

Hanze University of Applied Sciences Groningen (Hanze UAS) has extensive experience as a coordinating orginization with good management of projects from very large to very modest size. The project partners Hanze UAS, Woonstichting Groninger Huis, Gebiedscooperatie Westerkwartier and L'orèl Consultancy work closely together to carry out the project activities. The researchers of the project will also talk to a number of farmers in Nieuwolda and Westerkwartier, the Agricultural Society De Eendracht, Dotterbloem Foundation and the Association Sustainable Agriculture City and Ommeland to collect data for the model to be developed and the possibilities and limitations of various aspects of the AgroCycle concept. After grant allocation, the project will start with a kick-off meeting and the aforementioned partners will discuss the progress of the activities and results on a regular basis. The project has a lead time of one year. In the first phases, data collection and modeling have a central role, where the required data will be delivered by the various project partners. The data is collected by the researchers from Hanze UAS, who will also manage the data during the project. In addition to the exchange of data and information between the project partners, a large number of stakeholders will be involved in the final phase of the project (stakeholder game). For this, two joint project meetings will be organized.

1. INTRODUCTION

The 'AgroCycle' project focuses on closing material cycles on agricultural businesses through the use of local organic waste streams for the production of energy and fertilizers by means of anaerobic digestion. Local organic waste streams, such as grass clippings, natural or roadside grass, agricultural and household waste and the like, are converted together with manure into biogas and digestate by means of Anaerobic Digestion (AD). In many conventional systems, the biogas produced is used in a CHP plant for the production of electricity, which is injected into the grid. The produced heat is partly used in the fermentation process. The digestate, or remaining biomass after biogas is extracted, is often regarded as a residual or waste product; however, the feasibility of such systems, both environmental and economic, can be strongly influenced by the application and economic value of the digestate.

In AgroCycle, the digestate is reprocessed into green fertilizers. The nutrient cycle is thus linked to the production chain of energy. With the AgroCycle concept, a farmer can become self-sufficient in his energy demand and even become an energy supplier for the immediate environment. In that case, biogas is not used completely in a CHP plant, but is upgraded to green gas and transport fuel (bio-CNG or LNG) for agricultural vehicles. In order for this symbiosis of production techniques to succeed in practice, intensive cooperation between agro-farmers and dairy-farmers is required. Agro-farmers supply part of the bio-digester's input and receive green fertilizers at the end of the process, which serve as a replacement for artificial fossil fertilizer. AgroCycle assumes a cooperative of farmers with a minimum geographical spread and maximum diversity in the type of companies. In this way, the current waste and nutrient chain is replaced by a more sustainable and closed cycle, which can provide significant environmental benefits: reduction of environmental impact through the use of artificial fertilizer, reduction of dependence on fossil raw materials and reduction of CO_2 emissions.

In collaboration with the project partners, the economic feasibility and sustainability are examined, in which current techniques are combined with symbiotic systems to maximize renewability and/or sustainability. For instance, one can think of a combination of green gas, green fertilizers, green fuel and the production of heat and electricity (CHP) for the process. In collaboration with the farmers in the project, the scenarios can then be put into a practical case study. For the calculation of the scenarios, use is made of the existing 'BioGas Simulator' model developed by Hanze UAS to simulate the technical process of decentralized production of biogas, which is further developed by adding different techniques and practical knowledge from the project group. The AgroCycle concept consists of a combination of technology, collaboration from farmers, and supporting the business case. These have never been brought together before in theory or practice and thus contribute in a practical way to innovation within the agricultural sector.

1.1 Anaerobic Digestion

Large environmental benefits can be achieved with decentralized bio-digesters on agricultural farms, particularly when waste streams such as manure and roadside clippings are used locally for the production of green gas. Green gas leads to the reduction of dependence on fossil energy and the reduction of CO_2 emissions in the agricultural sector. Despite these environmental benefits, such projects are difficult materializing. Many small-scale bio-digesters on agricultural companies are faced with a difficult business case or even a negative business case. This is partly due to high biomass feedstock prices. Furthermore, the financial feasibility of a bio-digester is highly dependent on the use and economic value of the digestate. That is why AgroCycle is based on upgrading the digestate to green fertilizers. In addition to the often difficult business case, current anaerobic digestion systems are criticized for the use of energy crops, long transport distances for the supply of biomass and the energy-intensive process. These aspects are explained in more detail below.

Energy crops: Many bio-digesters are fed by energy crops, which are under fire because of competition with (animal) food production and other forms of land use, which is a considerable drawback in a densely populated country such as the Netherlands. Other disadvantages are the environmental effects of the intensive cultivation of energy crops, including the leakage of nutrients (Nitrate, Phosphates, etc.) when using artificial fertilizer. Also energy crops have a relatively low energy yield per unit of land compared to solar PV or wind, due to the low efficiency of the plant and AD process. That is why this project investigates the use of organic waste streams such as municipal pruning, cuttings and roadside, domestic waste and manure. Co-fermentation of manure with organic waste flows also has a higher yield than that of manure alone.

Transport of biomass: The local winning, collection and processing of organic waste flows underlies the 'AgroCycle' concept. In many analyzes of local biomass potential, the energy required for the transport from the location where the raw material is extracted to where it is applied is excluded. It is precisely this transport energy that strongly influences CO2 emissions from biomass. By local use of biomass, where it is extracted and processed on site, CO2 emissions from transporting biomass are reduced to a minimum.

Energy intensity of the process: The current bio-fermentation systems are not designed with chain integration in mind. For example, closing the nutrient cycle is barely taken into account. Production of biogas, fertilizer and transport are separate value chains with a high energy intensity across. The combination or integration of these processes into one circular system, which is aimed at in AgroCycle, leads to optimization of the whole value chain, which could lead to a much higher energy efficiency, lower environmental impacts, and a positive business case.

Demand management and networking: Agriculture is responsible for a large share of national energy demand and emissions within the Netherlands. Fermentation of manure and possible by-products can significantly reduce emissions and at the same time produce renewable energy. Unfortunately, many small digesters are having economic difficulties in staying afloat. The immediate reason for this project is to investigate the possibilities for improving bio-digester projects. In order to realize greater financial feasibility a joint digester with a cooperative of agricultural companies is being investigated in this project according to the AgroCycle concept. Making local bio-digesters economically attractive can have positive consequences for nutrient cycles, energy use and farm emissions. Up-to-date information about the operational management of farms and digesters is acquired through intensive cooperation with partners in the Nieuwolda and Westerkwartier area. The aforementioned areas are actively engaged in the concept of energy transition. The village of Nieuwolda has the ambition to become the most energy-efficient village in the Netherlands. Woonstichting Groninger Huis, the municipality of Oldambt, and Vereniging Dorpsbelangen Nieuwolda are the initiator of this ambition. With its network in Nieuwolda and knowledge in the field of energy transition, Woonstichting Groninger Huis is an important partner in the project. For the research in the Westerkwartier (municipalities of Grootegast, Leek, Marum and Zuidhorn) the Area Cooperative Westerkwartier is the other partner in the project. Area cooperative Westerkwartier connects green entrepreneurs, nature managers, knowledge institutions, governments and citizens in the region working on topics such as the green economy, sustainability and the bio-based economy. Furthermore, L'orèl Consultancy is involved as a project partner. L'orèl Consultancy has a lot of (technical) knowledge in the area of specific energy saving and energy management in the agricultural sector. Finally, the project partners mentioned will meet with a number of farmers in Nieuwolda and Westerkwartier, the Agricultural Society De Eendracht, Dotterbloem Foundation and the Association for Sustainable Agriculture City and Ommeland to collect data and to define the possibilities and limitations of various aspects of the AgroCycle concept.

Research question: Can a cooperative of farms become self-sufficient in energy and fertilizer use by using manure and organic waste streams for the production of energy, green fuel and green fertilizers by means of Anaerobic Digestion?

The project partners aim to link the nutrient cycle (from manure to digestate to green fertilizer) to a self-sufficient energy system (biomass to biogas to green fuel for processing the land) through the combined production of biogas and green fertilizers. The financial feasibility of a biodigester is highly dependent on the use and economic value of the digestate. This combined approach increases both feasibility and sustainability (environmental impacts and CO2 emissions). To explore the feasibility of this concept, the existing 'BioGas simulator' model (developed by Hanze UAS to simulate the technical process of decentralized production of biogas) is used. The model is based on 'industrial metabolism', which combines material and energy flow analysis, environmental and system analysis, life cycle analysis (LCA) and the NCW method. The model does not yet take into account the different possible production routes (value chains). Value chains are complex systems with many factors and variables. In the context of this project, the model will be further developed into an advanced simulation model that is needed in such a feasibility study. To this end, a literature study will be conducted into the different techniques for fermentation, production of biogas and processing of the digestate into green fertilizers. The possibility for deploying catch crops is also being investigated (desk study and exploratory research). In addition, specific data is required as input for the model, which is supplied by the partners involved. Water board and municipality are approached for data on the waste streams that are available for the fermentation process. The farmers involved enter into a more intensive collaboration with the researchers, in which they discuss the possibilities and limitations of various aspects of the AgroCycle concept. Hanze UAS brings this information together in the model. Part of the project is also the preparation of a business case, for which several discussion rounds (stakeholder game) take place with all parties involved.

1.2 Research focus

In AgroCycle the material cycle of nutrients is closed: manure and organic waste streams are converted into biogas and digestate by means of anaerobic fermentation. Bio-fermenters are generally put into operation for the production of biogas. The digestate that remains after production is regarded as a residual product. The digestate can be reprocessed into green fertilizers that can replace artificial fertilizer, which are again locally spread over the land in order to close the nutrient cycle. This has several positive environmental effects, such as reducing the leakage of, among other things, high concentrations of nitrates from chemical fertilizers into the environment and the saving in (fossil) energy required for the production and distribution of artificial fertilizer. To further reduce the use of manure, the role that catch crops can play is also examined. Catch crops can be used as buffer and border zones on fields. The use of catch crops ensures a higher nitrogen concentration in the soil, which means less fertilization is required. Through the buffer zones nutrients from fertilizers leak away less easily in the surrounding ditches. The nutrient cycle is closed more because fewer nutrients leach into the environment and nutrients naturally enrich the soil. Residues from these catch crops serve with their large energy potential as a raw material for the bio-digester (waste = food). The biogas produced during the fermentation process is used in the production process from digestate to green fertilizer and transport fuel, which requires heat and electricity. This creates a link between the nutrient cycle and the production chain of energy. This results in considerable CO2 emission reductions, mainly due to the savings in the transport of biomass. With sufficient scale level, there is even the possibility of supplying green gas to the environment. Optimizing the chain is only possible through cooperation between dairy farmers and arable farmers. This symbiosis, formed by a cooperative of farmers, underlies the AgroCycle concept. The manure that is produced on the dairy farm no longer needs to be spread over the land, but is processed into green fertilizer that is used at the arable farm. In turn, the arable farm also supplies biomass to feed the bio-digester.

In order to bring the AgroCycle concept to completion to the agricultural companies, preliminary research is required. In the form of a feasibility study, we expect to gain sufficient insights to be able to assess whether continuation of the initiative in the form of a practical case is useful. First of all, legislation and regulations are not taken into account and the technical, economic and sustainable feasibility is mainly looked at. In addition, at organizational level, the formation of a cooperative of farmers, with a shared business case is also important. The project also aims to contribute to this. Thanks to this practice-oriented way of working, the innovation process that the farmers in Nieuwolda and the Westerkwartier have already started is supported and further developed.

2. APPROACH IN THIS REPORT

Within this report the research approach and methodology used is based on Pierie et al 2018 [1], where the overall sustainability of the AD biogas production pathway will be analyzed in steps. These steps are based on the PESTEL analysis, for this report including PEOPLE, PLANET, PROFIT, and SPACE, which will be further discussed in this chapter.

2.1. System boundaries

Dutch regulation states that at least 50% of the feedstock used in an AD system must consist of manure (e.g. cow, pig, chicken manure), the remainder can be complemented by other biomass (e.g. harvest remains, catch crops, roadside grass, or maize) in order for the digestate to be used as fertilizer. Energy and material flows and their impacts are taken into account when they are in service of the AD system (e.g. production, processing, and transport), (Fig. 2.1) [2]. The embodied energy, the energy required for the construction of the installations and or the cultivation of crops is also incorporated. Within this research, mitigation regarding the replacement of current waste treatment chains (e.g. current manure storage and waste crop management) with an AD system and fossil fertilizer with green fertilizers are taken into account. Our analysis only considers the economic aspects of processing excess digestate. Emissions from digestate application to the field are incorporated [3]. Emissions from the soil are not included. Internal energy use is included where external sources of energy can be replaced with the energy gained from the AD system (Fig. 2.1). Additional economic costs or revenues saved or lost through the use of improvement options are taken into account as cash flows within the NPV. The current energy and fertilizer use (e.g. manure, fossil fertilizers) of farms are included in a theoretical case, for determining the effectiveness of a cooperatively owned circular symbiotic AD system. The costs and revenues of the AD system are based on prices and subsidies within the Netherlands [4].

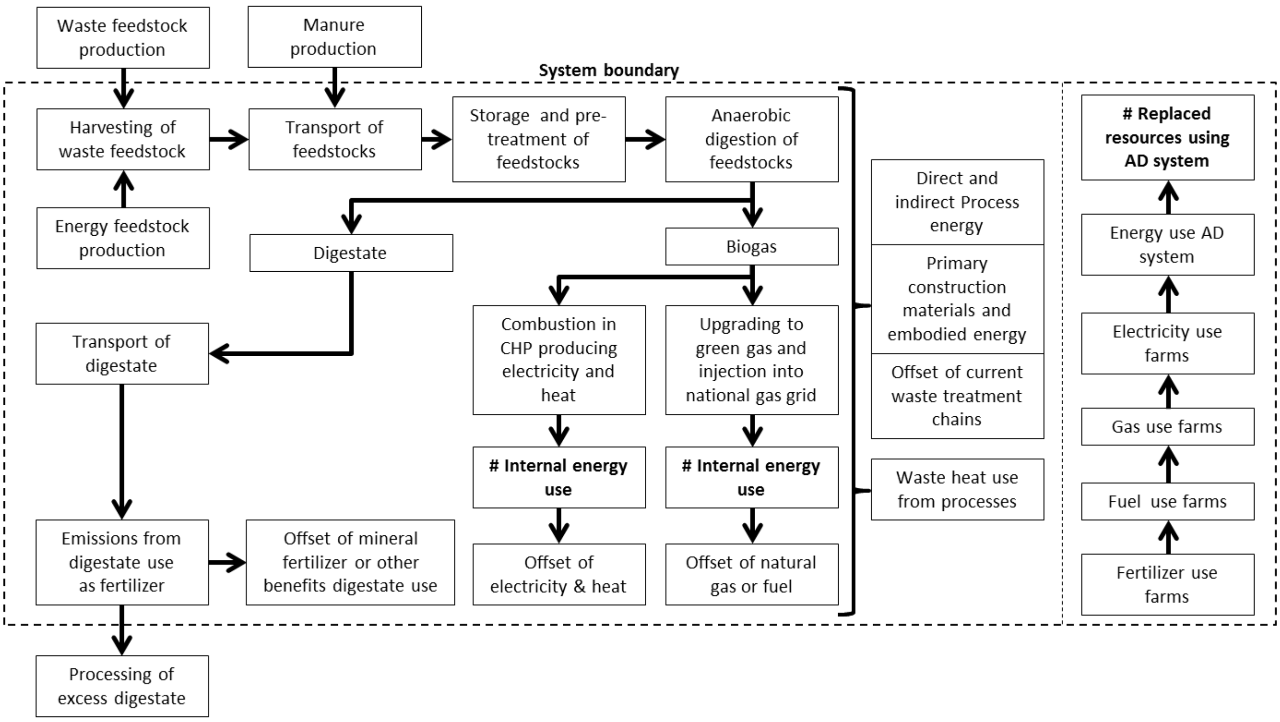


Fig. 2.1. System boundaries of biogas production and utilization, including aLCA

Using the circular symbiotic AD system in the theoretical case will replace current energy and fertilizer flows used on the farm

2.2. Steps performed within the analysis

The approach used in this research is constructed from a synthesis of literature and practical information which integrates physical, economic, and social indicators of sustainability together in one set of comprehensive and comparable expressions (or a label). The label of individual REPP's, which indicates the expressions used within the new approach in a comprehensive overview, can be compared to other analysis (of the same or other REPPS) already performed. Furthermore, the label together with the modular design can aid in optimizing REPPs, based on the indicators. The use of the approach also requires a logical and research oriented approach as every local energy system is often different in design and location. Therefore, the main rules described in this method are similar between pathways; however, the detail for specific REPP's can and most likely will differ. In this section the main steps for performing an analysis on a REPP will be discussed using AD biogas production as example (Fig. 2.2).

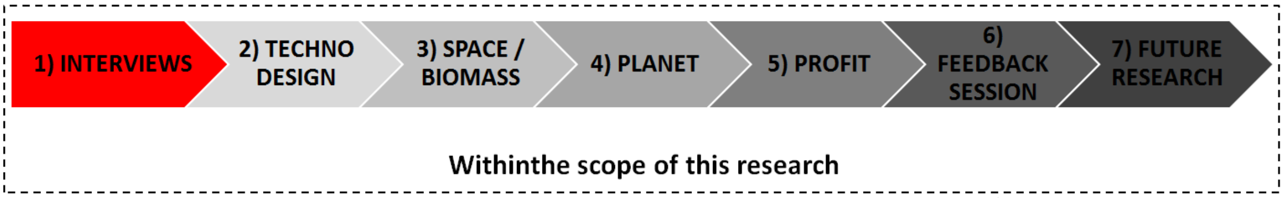


Fig. 2.2. Process flow measuring the sustainability of a (Renewable) Energy Production Pathway

STEP 1 (PEOPLE): Interviews (Kitchen table conversations)

One of the data collection steps within the Agro Cycle project is the collection of field data from farmers through the use of kitchen table conversations. Before a session a questionnaire is sent out asking information on the consumption of energy and fertilizers on the farm and potential feedstocks for AD biogas production. During a session we discuss if farmers are willing to operate in cooperation and are willing to invest in an AD system.

STEP 2 (DESIGN): Design of the energy production pathway

The analysis will start with determining the main components and main flows of the REPP, using the modular approach, where a specific structure is followed. Within the modular approach, the REPP is defined as a collective of physical processes working together to achieve a common goal (e.g. biogas or green gas production). These individual physical processes are called sub-modules and are assigned to groups that perform the same physical process called modules (Fig. 2.3). The REPP will be built up out of a succession of sub-modules in logical order forming a chain which, for instance, could result in the Anaerobic Digestion green gas production pathway depicted in Fig. 2.3. The aforementioned approach will allow several arrangements of sub-modules to form different production pathways; including multiple energy sources (e.g. wind, solar PV, geothermal, etc.). In a later stage (optimization) the modular approach can be used to design the optimum production pathway to fit particular cases, by changing, adding or removing individual sub-modules during the modeling (or planning) process.

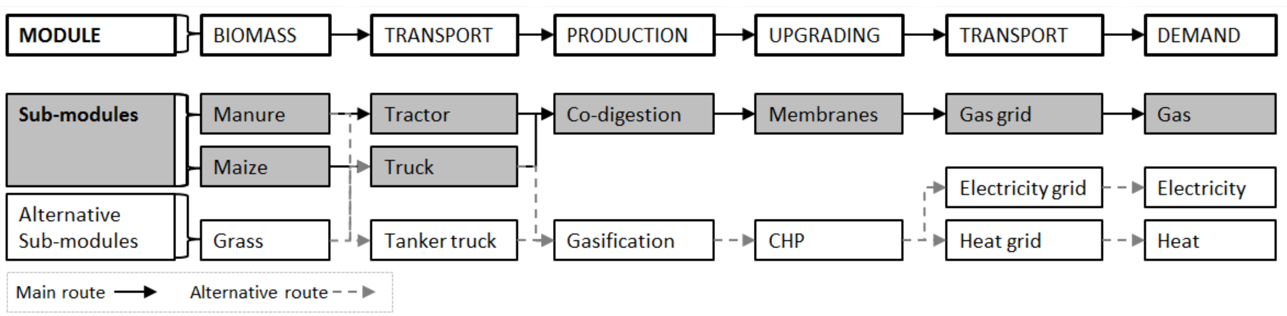


Fig. 2.3. The main modules and sub-modules used in an example green gas production pathway

STEP 3 (SPACE): Determining local energy availability and space use

A REPP interacts with its surroundings and has an impact on space or the surrounding area. These impacts determine the amount of renewable energy which can be produced or placed within a certain area. The space required per renewable energy source or energy system is determined by the energy density of the fuel source. For instance, biogas yield of an AD system using local biomass depends on the biomass potential within the selected area. For collecting solar and wind energy, space is also an important requirement for determining yield (Fig 2.4), together with local solar irradiance and wind speeds. The needed space of the REPP must be in line with the available space in the selected area and align with other uses of this space (e.g. agriculture, residential). Often, (within the Netherlands) when space is utilized for a REPP it had a previous function, therefore, space can be seen as valuable resource and must be allocated with care. There is the option to import energy from other locations; however, this only shifts the land use allocation to another region.

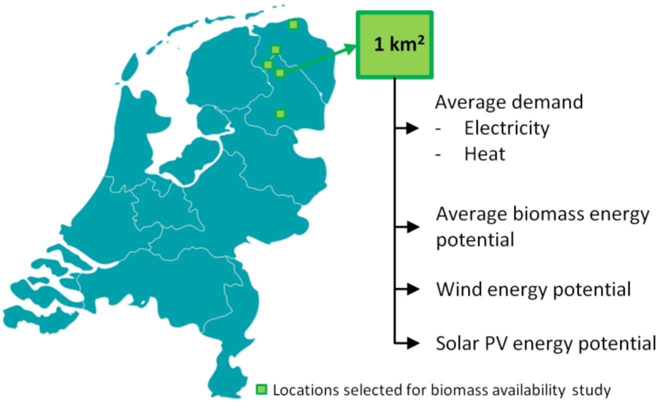


Fig. 2.4. Determination of average biomass availability (Chapter 5)

STEP 4 (PLANET): Determining the environmental impact

The impact on the PLANET or environmental sustainability is determined per sub-module. Within each sub-module (e.g. Co-digestion in Fig. 2.3), one main physical process of the energy production system is described. Every sub-module will be capable of determining three environmental impact indicators. The indicators used are; the (Process) Energy returned on Invested (P)EROI, indicating the efficiency of the chosen scenario; the carbon footprint (GWP100), indicating global warming potential; and the Eco Indicator ReCiPe 2008, indicating the overall environmental impact to the ecology, nature and human health. Taken together, these indicators can give a clear overall impression on the efficiency and environmental sustainability of a REPP. To determine the aforementioned factors, each sub-module is separated into four levels (Fig. 5); level one, the primary (mass) flow level; level two, the direct energy and material level; level three, the indirect energy and material level; and level four, the embodied energy level. When looking to an AD installation: Primary mass flows are defined as raw materials (e.g., biomass, biogas, di-gestate and/or losses of the previous flows), which run through the system: Direct energy flows are used during the handling and conversion process of raw materials towards a finished product (e.g. diesel, electricity, heat, fertilizer): Indirect energy and material flows are required for the production of the direct energy and material flows (e.g. production of diesel): Embodied energy and material flows are required for the construction, maintenance, and deconstruction of the installations used for processing the primary flows (e.g. digester). Each level will be described through the use of an existing method and will require its own calculations (Fig. 5). Within this dissertation the new approach is integrated within a mathematical (what if) model called the BioGas Simulator, specified for calculating the sustainability of farm scale biogas production pathways.

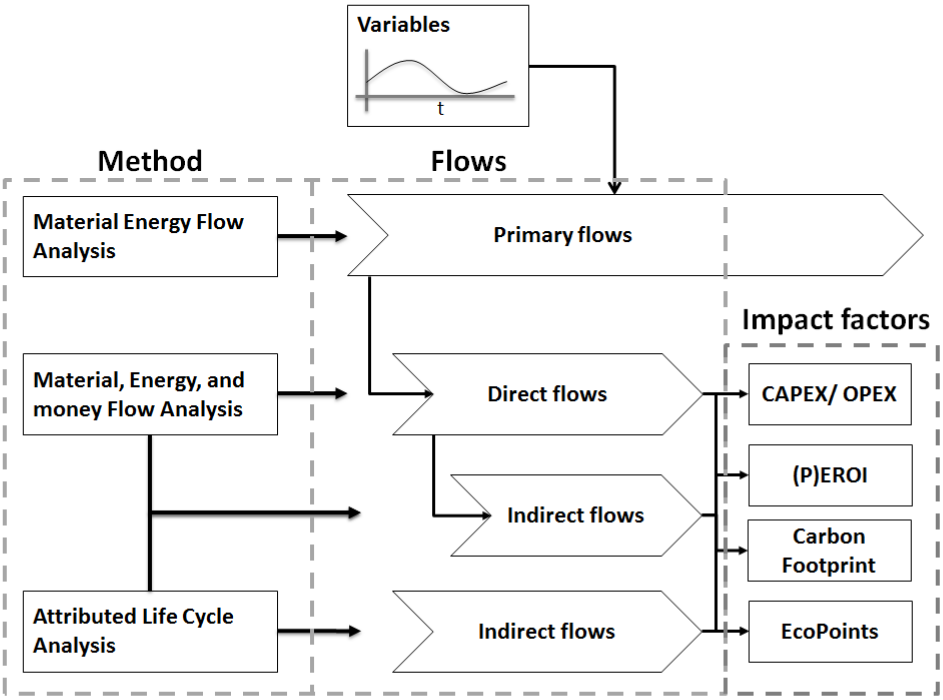


Fig. 2.5. Structure of a single sub-module based on dynamic MFA / MEFA / LCA

The (Excel) BioGas Simulator or EBS model is capable of calculating the economic cost, energy efficiency, carbon footprint, and environmental sustainability of small (farm) scale Anaerobic Digestion (AD) biogas production pathways (2000 up to 50000 Mg/a biomass input). The results from the model are expressed in four main indicators; the economic cost in Net Present Value (NPV) and (economic) payback period; the efficiency in (Process) Energy Returned On Invested; the carbon footprint in Global Warming potential 100 year scale; and the environmental impact in EcoPoints. The indication of sustainability in four clear indicators gives an understandable reference for comparison with other scenarios and allows the research of several aspects of the biogas production pathway. The EBS model is constructed around a clear methodology, comprised of the industrial metabolism concept, modular approach, Energy and Material Flow Analysis, Life Cycle Analysis, and Net Present Value analysis. The modular approach separates the biogas production pathway into individual physical processes, which makes the model more transparent, flexible in use, and programmable with different settings. Overall, the EBS model can help shed insight on the sustainability of specific biogas production pathways and help indicate options for improvement.

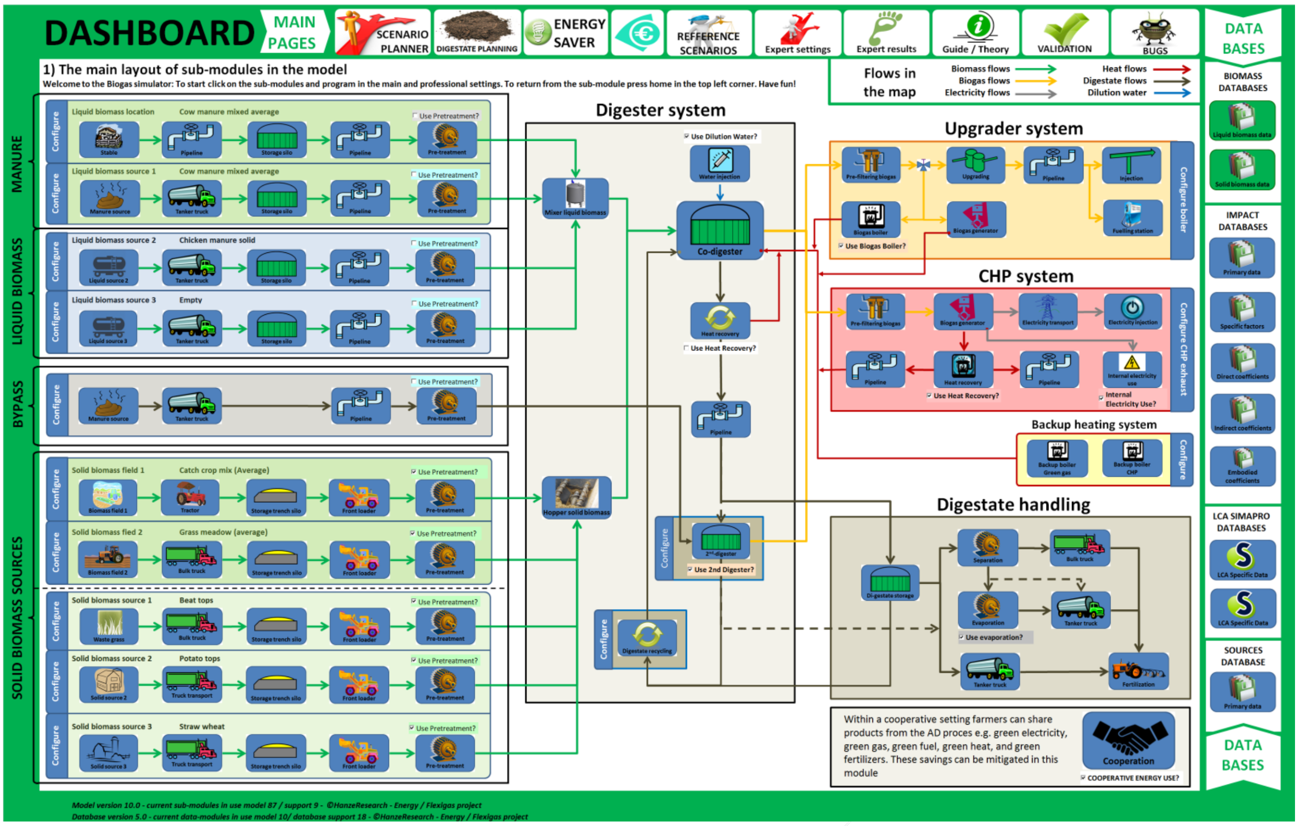


Fig. 2.6. The main layout (MEFA) of the biogas production pathway in the EBS model

STEP 5 (PROFIT): Economic cost calculations and business case

An important element within every business case, amongst others, is profitability. Indicators for profitability include payback period, Net Present Value, and/or Internal Rate of Return. Within this research, the Net Present Value (NPV) method was selected as it is a commonly used indicator for economic feasibility and indicates the overall profitability of an investment over its economic lifetime. To determine the NPV within the new approach firstly, CAPEX, OPEX, and revenues are included in the MEFA element of the new approach (See STEP 4, Fig. 2.6.). CAPEX represents capital investments in the REPP (e.g. digester installation, upgrader, CHP), OPEX the operational expenditures (e.g. cultivating or purchasing biomass, electricity, diesel), and revenues the sales of products (e.g. green gas, green fertilizers). Added to this are other important factors that make up the cost of capital (e.g. interest, inflation, taxation). Combined the aforementioned factors represent the cash flows in the system which will be used in the NPV analysis to come to the final NPV indicator. NPV depends solely on the forecasted cash flows of the project and the opportunity cost of capital. The general rule of thumb is if the NPV is positive “invest” and if it is negative “don’t invest”. Setting up a business model of a REPP requires insight in economics, stakeholders, regulation, services provided etc.

STEP 6: Validation of the Business case (kitchen table)

We are going to validate the business case by presenting it to business experts and farmers and then recording their opinion about the validity and reliability of the business case. Expert opinion is a well-established method for validating the designed business case.

3. STEP 1: INTERVIEWS

The first step in the analysis was the gathering of information regarding the farming process and opinions of farmers regarding renewable energy and then in particular AD biogas production. Within the Agro Cycle project, eight farmers are involved and visited for a so called kitchen table discussion; additionally, a mechanization company that provides farming equipment and services was also contacted and interviewed, to provide additional insight in the fuel use of agricultural machinery. Before the discussion takes place a questionnaire is sent to the farmers to indicate and collect information regarding energy and material flows required in the farming process (Appendix A Table A-1). The data acquired through the questionnaire are compared to the data already in the Biogas Simulator (Based on average numbers of farming in the Netherlands). During the kitchen table discussions focus is placed on the opinion of the farmer regarding a Symbiotic AD system and the willingness to participate in an AD cooperation sharing feedstocks, green fertilizers, energy, and fuel. Firstly the concept of the Symbiotic AD system is explained (Appendix A fig. A-2) followed by an in depth discussions on possible drawbacks and benefits (following SWAT), (Fig. 3.1).

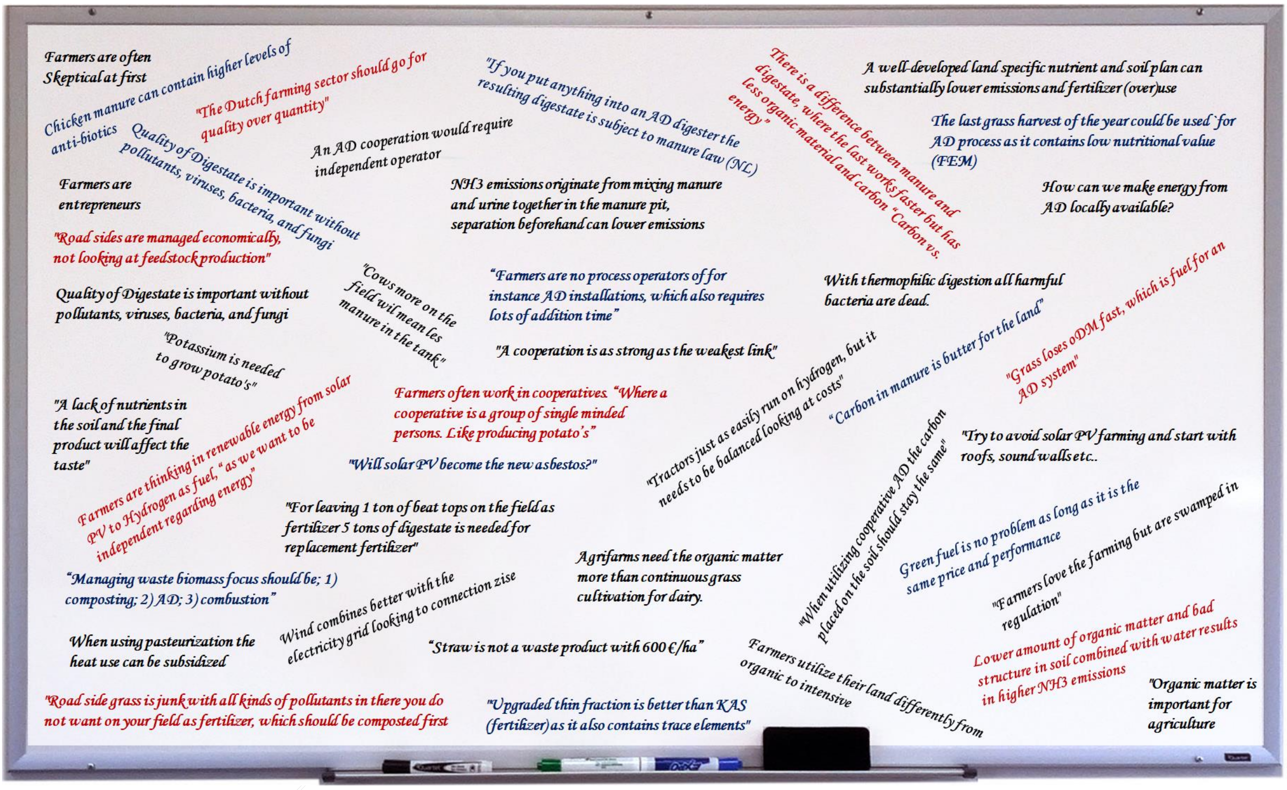


Fig. 3.1. Feedback from farmers during kitchen table discussions

From the interviews with the farmers a wealth of information was gathered for subjects directly related to the project but also many more subjects indirectly related to the project but also with the focus of lowering the overall impact of farming practices. One of the notions focusses on the separation or cooling of manure directly after deposition in the manure pit. This to lower NH3 emissions but also to create a dry product which can be shipped to a digester installation with more ease compared to liquid manure. Also, notions were made for replacing diesel with hydrogen fuel cell powered tractors. Overall, the collective awareness regarding renewable energy was high within the interviewed group of farmers. On the other hand the farmers indicated that focus on fertilizer and land use with in particular soil quality will become and already is a very important element in the farming process. When using AD in this line of thinking, additional carbon is removed from the system as manure and feedstocks normally used for fertilization is being processed into energy and digestate. Many farmers have doubts on adding this additional step of carbon extraction as it can further degrade soil quality. For permanent grass land this is less a threat as for agricultural fields, especially when removing harvest remains, soil quality could deteriorate. On the other side farmers are willing to think of and maybe even participate in an AD cooperative as there are many renewable advantages. Within this cooperative thinking it is important to have a common goal in the cooperation and to include strong partners as “a cooperation” is as strong as its weakest partner. Additionally, digestate and green fertilizer quality needs to be guaranteed, therefore, not containing pollutants, chemicals, bacteria, viruses, or fungi. Farmers also indicated the need for balance in the system where not all the biomass is used, extracting all the carbon from the land, but only the required biomass to fulfil the needs of the cooperation, looking at energy. Also, the AD system should be owned and operated by an independent partner in the cooperation with specific knowledge on owning and operating an AD system, this to let farmers focus on their profession. Overall, the farmers interviewed are already very active and knowledgeable in the field of renewable energy production, however, they indicate that there is still lack in knowledge how to optimize and combine both energy production and farming practices. Within this regard, research on increasing the energy efficiency of farming practices can also help in lowering farming emissions.

4. STEP 2: SYSTEM DESIGN

Within this chapter the technological infrastructure and design of the farm scale AD biogas production pathway will be discussed.

4.1. Introduction on Anaerobic Digestion

Anaerobic Digestion (AD) is a process by which wet organic material can be biologically transformed into another form in the absence of oxygen [5]. The diverse microbial populations degrade organic waste, which results in the production of biogas and other organic compounds as end products called digestate [6]. AD has been applied as an effective technology for solving energy shortage and reducing environmental impacts [7]. The environmental impact can be reduced by preventing access methane (present in biogas) from entering the atmosphere due to the sealed environment of the process, and combustion of the same will produce carbon-neutral CO_2 (no net effect on atmospheric CO_2 and other GHGs when using biomass), and it does not contribute to ozone depletion or acidic rain [5]. AD is a synergetic process and a series of metabolic reactions which occur in steps, are involved in this process [8]. Initial material is continuously broken down into smaller units by specific group of micro-organisms in individual step, with the main phases; hydrolysis, acidogenesis, acetogenesis, and methanogenesis (fig. 4.1).

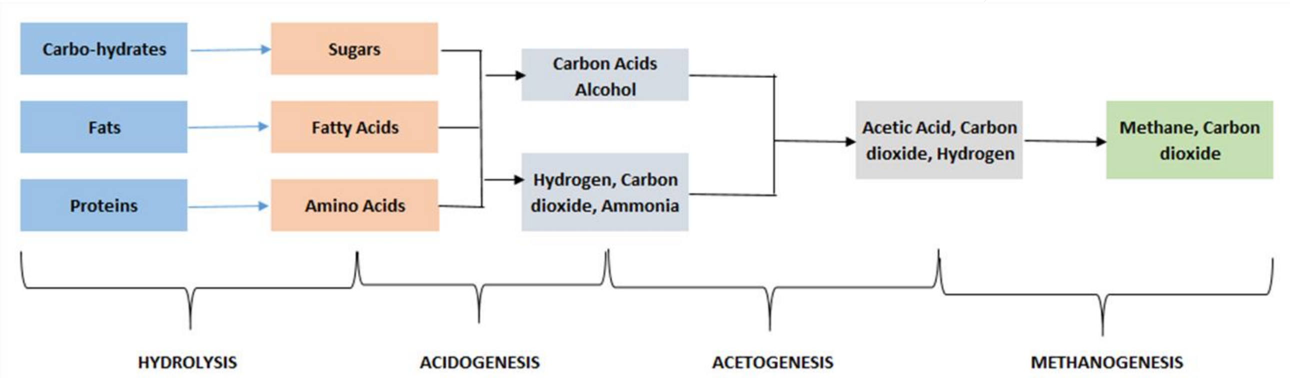


Fig. 4.1. The main process steps of an Anaerobic Digestion

Co-digestion of wastes is suitable for improving biogas production [9]. Also, inoculation of fresh feedstock speeds up the reaction process [8]. Manure is an excellent inoculum as it has high water content, high buffering capacity, and a wide variety of nutrients which are necessary for optimal bacterial growth [9]. Co-digestion also facilitates a stable and reliable digestion performance and a digestate of good quality [5]. AD can be classified into 3 types; psychrophilic (< 25°C), mesophilic (25-45°C) and thermophilic (45-70°C). Generally, mesophilic temperature is more suited as the reaction is more stable and requires small energy expense [5]. Depending on the type of reaction the “retention time” also differs [5]. The retention time for mesophilic reaction is 30 to 40 days [10]. So, the assumption was made for a co- digestion, mesophilic reaction which takes at 42°C for 35 days.

4.2. AD System used

All scenarios will use the same AD plant setup as a starting point, (Fig. 4.2). The AD system, with a feedstock throughput of 20000 Mg/a (Section 5), is stirred and heated to maintain mesophilic temperature. When required, feedstocks are mechanically pre-treated, screened for foreign debris (e.g. plastics, stones), and/or pasteurized (Table 4.1). Transport of biomass is conducted by truck, loading and unloading is incorporated. Part of the produced biogas is used in a small boiler to produce the needed heat for the digestion process. The remaining biogas is upgraded to green gas through the use of a highly selective membrane upgrader system [11]. The green gas is injected in the national gas grid (Fig. 4.2). A gas pipe over a distance of one kilometer is used to transport the green gas from the production site to the injection station. The electricity use for the AD system is imported from the national electricity grid. The digestate is used on site as fertilizer on the pastures. The NPV of the business case, over a technical lifetime of 25 years and an economic write off period of 15 years, is based on economic factors within the Netherlands (e.g. energy prices, CAPEX, OPEX) [12-14]. Subsidies for green gas or electricity production are given per kWh of energy injected into the grid [4], (Appendix II).

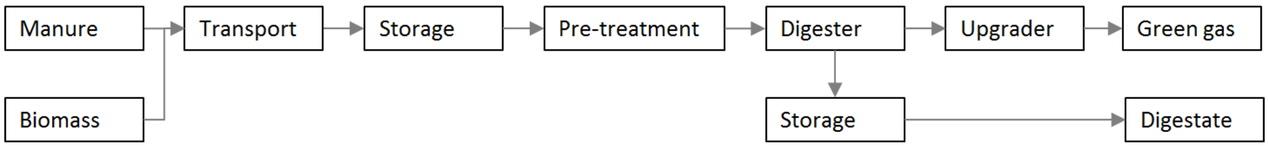


Fig. 4.2. Main green gas production pathway of the Normal scenario

4.3. Analysis of technologies

The AD Process can be defined as a series of actions or steps taken to reach a particular goal or end product. Within this process specific technologies are used in a specific order to reach the particular goal or end product. Thus, if a process has a single goal, there can be multiple technologies to achieve that goal. Similarly, for the symbiotic AD system described above, there are several processes and each process has several technologies. The processes are fixed, whereas the technologies are flexible, which will have to be looked into for synergy, which in turn could result in a more environment friendly and productive process. Within this section the technologies for biogas production and multiple technologies for biogas upgrading and digestate upgrading are discussed regarding technical properties.

4.3.1. Digester

The digester (Fig. 4.3a) is the heart of an AD process, where the anaerobic digestion of biomass takes place. The digester requires technologies for pumping in and out materials, mixers for proper mixing of raw materials inside the digester (Fig. 4.3b), and heaters for heating the biomass. Chopper pumps are used for breaking down bulky materials into small pieces before entering the digester. They also have the capability to handle different types of materials. Mixers are used for stirring the biomass (e.g. bladed, Fig. 4.3c). Within this research single tank AD is selected and used for the main AD digestion system, there are other technologies available (e.g. plug flow), however, they were not capable of handling the current selection of feedstocks (due to water content).

Fig. 4.3a. Digester tank

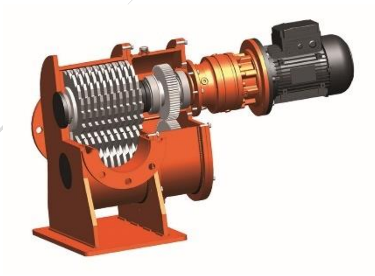


Fig. 4.3b. Chopper Feedstock Pump

Fig. 4.3c. Stirrer inside digester tank

Table 4.1. Energy use of main main green gas production pathway of the Normal scenario

Technology	**Energy use**	**Unit**	**E= electricity H = heat F=Fuel**	**Source**
LCA SimaPro transport	2.75	MJ/Ton.km	F	[15]
Hammer mill pre -treatment	0.02	MJ/Kg FM	E	[16]
Anaerobic Digestion system	0.0330	MJ/Kg FM	E	[17]
Mesophilic concrete round tank AD	0.2500	MJ/Kg FM	H	[17]

* Based on a 26 Ton load capacity of the truck
* Green fuel is 54.2 MJ/kg
* Diesel is 35.8 MJ/L

4.3.2. Filtration of Biogas gas

The gas obtained from the digester is known as ***"biogas"***, which is a mixture of several gases. Also included in the mixture are harmful gasses (e.g. hydrogen Sulphide (H_2S) and water vapor), that need to be removed before combustion or upgrading, as they are corrosive in nature and their presence may cause severe damages to various components [18]. Activated carbon is an effective measure to remove both these gases by adsorption. However, the activated carbon must have different sizes of pores and different coating to adsorb H_2S and water vapor selectively [18]. The model uses activated carbon with an efficiency of 99.80%.

4.3.3. Upgrading Biogas to green gas

Biogas produced with AD has a low methane content which needs to be improved to replace fossil natural gas. Biogas upgrading is a step where mainly CO2 and other trace gasses (e.g. N_2, O_2) are separated from the methane, which raises the calorific value of the gas [19] and makes it similar in quality as natural gas. The upgrading process helps biogas to replace natural gas in grids as green gas and replace fossil vehicular fuel. For The Netherlands, the methane quantity should be above 80% in the gas grid [20, 21]. The various upgrading technologies considered are pressure swing adsorption, membrane separation, amine scrubbing, water scrubbing, and cryogenic separation (Table 4.1).

1) Pressure Swing Adsorption (PSA): Pressure swing adsorption (PSA) is based on a principle that under increased pressure certain gases can be separated from others by adsorbing to solid surfaces due to their molecular size [21], (Fig. 4.4). An efficient process control, high costs of investment and operation are some of the demanding features of this process [22]. The adsorbing materials are generally activated carbon or zeolites. The upgradation plant needs to have several vessels packed with the adsorbents in parallel. When one is saturated flow is directed to another vessel. Sequential decrease of pressure does the regeneration of the adsorbents [21].

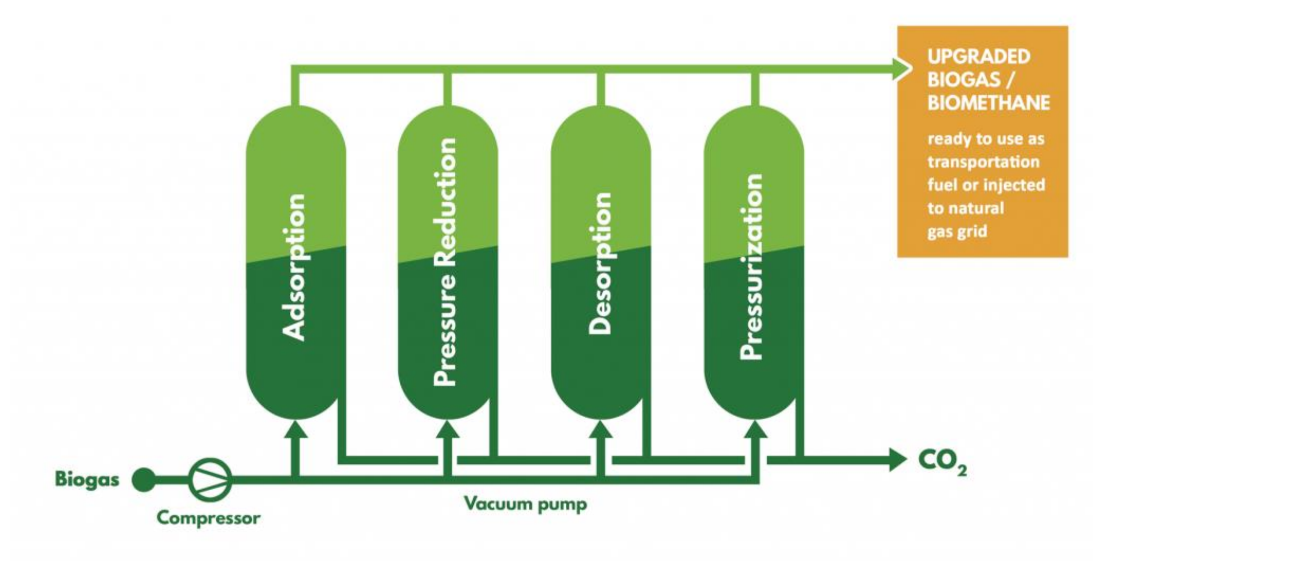


Fig. 4.4. Biogas upgrading using pressure swing absorption [23]

2) Membrane Separation (MS): Membrane separation (MS) is an energy efficient, low cost, and easy process of separating methane from CO_2.The biogas is passed through a membrane and CO_2 passes through it while methane is retained on the inlet side [22], (Fig. 4.5). Polymeric, inorganic and mixed matrix membranes are generally used for this separation.

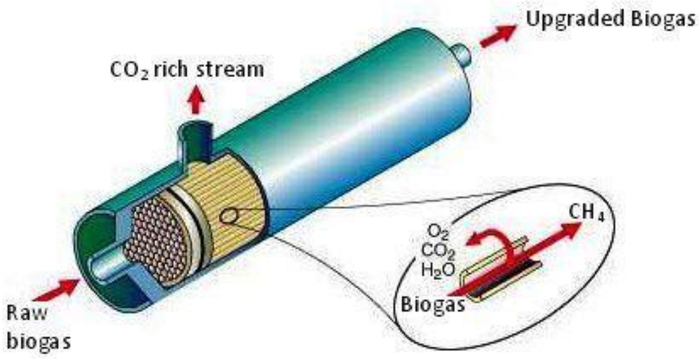


Fig. 4.5. Biogas upgrading using highly selective membranes [11]

Water Scrubbing (WS): uses the fact that CO_2 is more soluble in water than methane [21]. Therefore, at higher pressure and/or lower temperature the solubility of CO_2 will increase. The biogas is compressed and fed to a water column where CO_2 dissolves resulting in a gas from outlet which has rich methane content (Fig. 4.6). Regeneration of water is done by reduction in pressure or by air-stripping [21, 22].

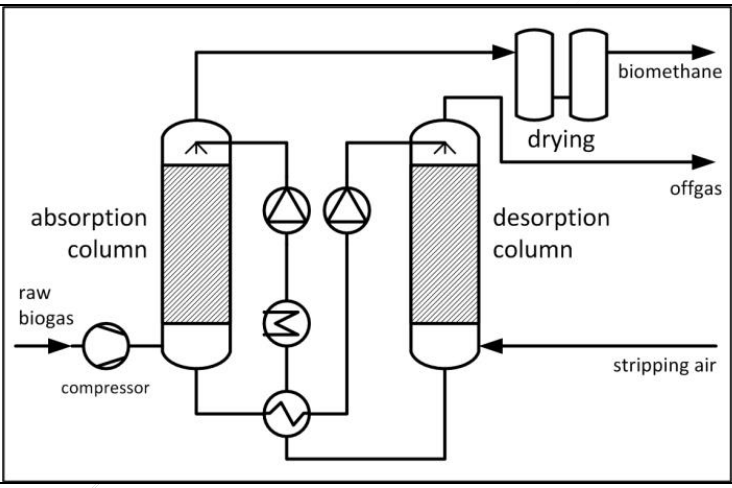


Fig. 4.6. Biogas upgrading using pressurized water scrubbing [24]

Amine Scrubbing (AS): Amine scrubbing is also regenerative in nature. The most common amines used are monoethanolamine (MEA), diethanolamine (DEA) and methyl diethanolamine (MDEA). The raw biogas goes through the absorber where CO_2 is absorbed and when temperature is increased CO_2 gets separated from the waste amine solution [22]. This process requires a high amount of heat [21] and overall is comparable with water scrubbing but then using another absorbent (Fig. 4.6).

Cryogenic Separation (CS): CS is a very energy intensive process which uses the different condensation temperatures of methane and CO_2 to separate the two; by maintaining a constant pressure and sequentially decreasing the temperature [21, 22], (Fig. 4.7).

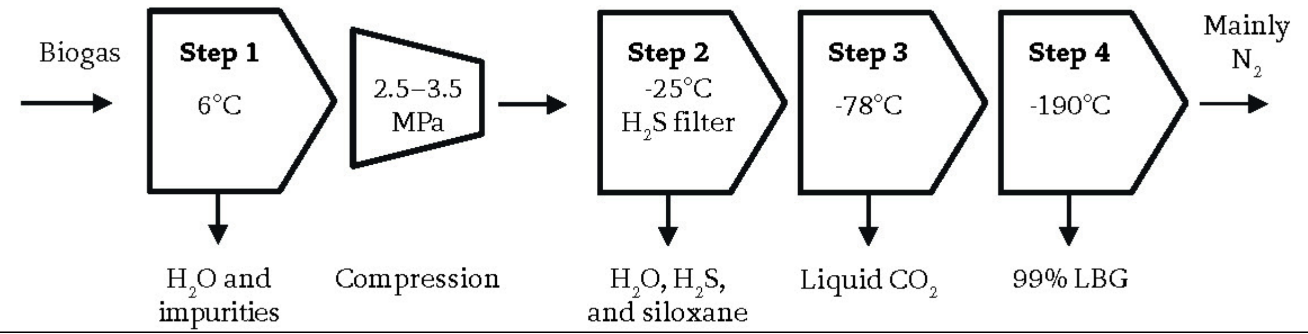


Fig. 4.7. Biogas upgrading using a cryogenic separation process [25]

All the above methods have their own energy requirements with different levels of purity obtained. But, all of them produce upgraded gas of quality at par required in the Dutch grid. A part of methane is also lost during the processes. The following table lists the values associated with the methods.

Table 4.2. Parameters for Upgrading Technologies [14]

Process	Energy Required (kWh/Nm3 of raw gas)	Efficiency (%)	Methane Purity (% of CH4)	Methane Loss (%)
PSA	0.23	93.20	83-99	2-4
MS	0.18	95	90-98	2
WS	0.30	95.70	96-98	1-2
AS	0.15 0.75 (heat)	97.70	97.5-99.5	<0.1
CS	0.28	96.70	98	<0.5

Biogas upgrading: The biogas is upgraded to green gas quality using upgrading system, which removes most contaminates (CO2, Hydrogen sulfide, oxygen etc.), (Table 6.3).

Table 4.3. Energy use of biogas upgrading technologies

Technology	Energy use	Unit	E= electricity H = heat	Source
Pressure Swing Absorption	0.83	MJ/Nm3 Biogas	E	
Membrane Separation	0.648	MJ/Nm3 Biogas	E	
Water Scrubbing	1.08	MJ/Nm3 Biogas	E	
Amino Acid	0.45	MJ/Nm3 Biogas	E	
	2.7	MJ/Nm3 Biogas	H	
Cryogenic Separation	1.01	MJ/Nm3 Biogas	E	

4.3.4. Combined Heat and Power Unit (CHP)

Combined Heat and Power (CHP) units are capable of transforming filtrated biogas into electricity and heat. CHP can be used in an AD plant site to take care of the internal energy needs. The use of a convenient CHP unit which can use biogas as fuel will reduce the dependency on fossil fuels and thereby reduce the carbon footprint of the system. There are several types of CHP units which run on biogas. Some are still under development to use biogas as fuel. Catalog of CHP Technologies by USEPA 2015 [26], gives an insight into the type of CHP units which can be made to run on biogas. A brief discussion about the same is presented below.

Steam Turbines: Steam turbines work on overheated steam produced in a biogas boiler, which is converted into mechanical energy in a steam turbine and then in electrical energy in a generator. These systems require a huge set-up and have high start-up times depending on the size. However, they have high efficiency combined with long working life and reliability [26]. Generally, solid biomass like wood and straws are used as fuel source in these particular systems.

Gas Turbines: Gas turbines can operate on biogas where the combusted mixture of air and biogas expands over a turbine and provides shaft power to run the generator. Gas turbines have high reliability, low emissions and have high flexibility. However, they have lesser efficiency than the above options [26]. Their efficiency suffers further at low load. Often in modern gas operated power plants gas and steam turbines are combined to further increase efficiency. Additionally, micro-turbines are small gas turbines. They come at high costs and have relatively low mechanical efficiency. Their compact size and low emissions are a benefit though [26].

Fuel Cells: Fuel cells are a relatively new technology. They produce electricity through electrochemical process where hydrogen is used as a fuel. Fuel cells have the capability to operate for extended periods, provided they have constant supply of hydrogen. They are clean, quiet and efficient. There are 4 primary types of fuel cells:

1) Phosphoric Acid Fuel Cells (PAFC)
2) Proton Exchange Membrane Fuel Cell (PEMFC)
3) Solid Oxide Fuel Cell (SOFC)
4) Molten Carbonate Fuel Cell (MCFC)

Biogas can be used for the production of hydrogen which in turn can be used in fuel cells. Fuel cells are becoming more popular for use in energy systems [27, 28], A. Baldinelli et al and N. Chatrattanawet et al [29] provide an insight of various reforming processes for a fuel cell running on biogas. *Fuel cell Energy* and *BloomEnergy* have fuel cells systems which can work with natural gas or refined biogas. *BloomEnergy* fuel cells are solely for producing electricity with no data found for waste heat utilization. The *Fuel cell Energy* system is currently operating on a dual fuel system of biogas from AD and natural gas, so that shortage of biogas would not hamper the energy generation [29]. The existing fuel cells of *Fuel cell Energy* work on biogas obtained from breweries, waste water treatment plants and waste food processing. No clarification was obtained about their compatibility with biogas obtained from AD of agricultural waste.

Reciprocating Engines: This technology is commonplace for mobile uses like trucks, trains, automobiles in varied ranges of power output. They are considered a mature technology and reasonably low-cost. The main advantages of these systems are fast start-up time, low investment, better load following, and easy maintenance [30]. The overall efficiency of a CHP unit can reach up to 86% with an electric efficiency up to 35%. The ability to use biogas as fuel, make CHP units an attractive option commonly applied in AD installations. However, engines often require periodic maintenance which increases costs.

4.3.5. Digestate Treatment

Digestate is a “by-product” of the AD process. They are the residues from the digester after biogas is extracted, which contain valuable mineral resources and hence, can be used as fertilizers. Digestate, amongst others, contains minerals like nitrogen, potassium, phosphorous calcium, which can be used, effectively, as a substitute for chemical fertilizers [30]. To produce fossil fertilizer quality, however, the digestate needs to be processed and upgraded. Often, the digestate is separated into solid and liquid parts. The solid fraction generally has more than 18% of dry matter, while the liquid has 2-6% of dry matter [30]. These individual fractions be upgraded further decreasing the water content making it more compact and giving it higher quality. Separation is either done by screw press, decanter centrifuge, flocculation, or belt press filter [31, 32]. After the separation liquid and solid fractions can be treated differently to decrease the water content. For solid fraction these methods can be drying or compacting [32] and for liquid fraction vacuum evaporation or reverse osmosis [31].

Screw Press Separation: In this separation digestate is introduced into a drum screen by a screw conveyor. The screen width varies and particles with a greater size get retained while more liquid passes through along with smaller particles from the screen. Remaining solids are separated by the screw conveyor at the end of the drum screen (fig. 4.8).

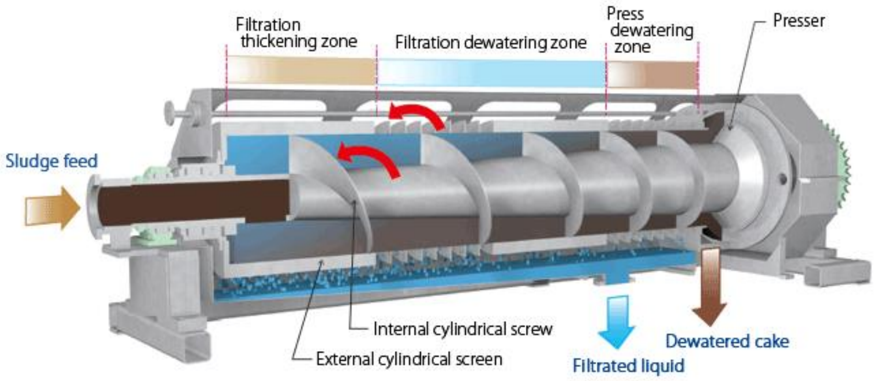


Fig. 4.8. Screw Press Separator [23]

Decanter Centrifuge: Within a decanter centrifuge an outer casing drum rotates with respect to an inner screw conveyor. The digestate is introduced in the middle of the drum through a drive shaft. Solid particles gather at the encasing drum's surface and are pushed out by the screw conveyor. Whereas, the liquid is squeezed out of the slits in between drum and screw conveyor (fig. 4.9).

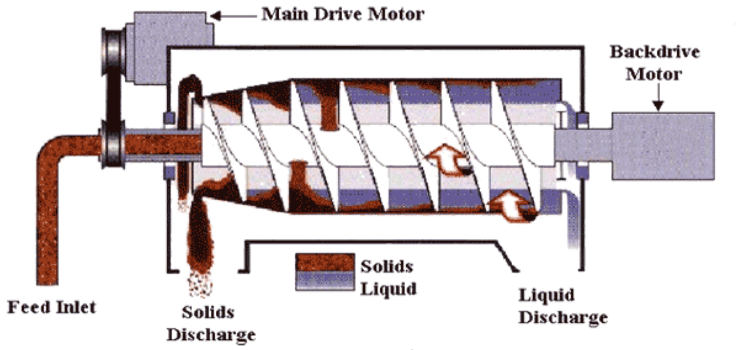


Fig. 4.9. Decanter Centrifuge [24]

Belt Press Filter: In the belt press filter the digestate is compressed between two filter belts which in turn run between rollers. The increased compression drives out the liquid with small particles of solids while a large chunk of solids is retained till the end where the belts separate and then they are scraped off (Fig. 4.10).

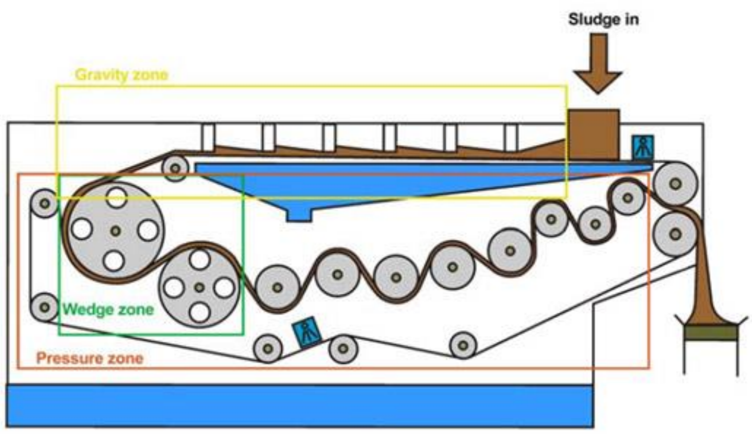


Fig. 4.10. Belt Press Separator [25]

Table 4.4. Digestion separation technologies

Technology	Energy use	Unit	E= electricity H = heat	Source
Screw press	0.00162	MJ/kg	E	
Decanter centrifuge	0.0144	MJ/kg	E	
Belt press	0.0032	MJ/kg	E	

4.3.6. Further Separation of Liquid Fraction

The liquid fraction can be processed further to separate out those small solid fragments which were not separated earlier. Also, in this fraction the ammonia can be removed as they can cause unpleasant odors and nitrogen pollution in farm lands.

Vacuum Evaporation: The liquid fraction obtained after the initial separation through the above 3 methods still contains solid particles from 1-8%. Vacuum evaporation is one of the ultra-filtration techniques which separates the remaining solids. The process can use the heat from the CHP. Within the vacuum evaporation process the boiling point of water is reduced to 40-70ºC, thereby reducing the thermal energy needed, for evaporating the water. Additionally, acidic scrubber removes ammonia. Finally, the water vapors are condensed to obtain clean water which can be recirculated for further usage.

Ultra-Filtration and Reverse Osmosis: This process uses membrane separation technique to obtain clean water. The liquid fraction after separation goes through a membrane separation (ultra-separation). The waste flow (retentate) is removed while the remainder (permeate) goes further for a double reverse osmosis process. During the first reverse osmosis most salts and dissolved substances are removed. But ammonia is not held back. So, before the second reverse osmosis sulphuric acid is introduced to permeate from the first reverse osmosis. This turns the ammonia to ammonium, which is then removed in the second reverse osmosis.

Ammonia Stripping: This process removes the ammonium from the digestate. Separation of solids before stripping is done, but the water is not as clean as membrane separation or vacuum evaporation. The liquid fraction is heated and sodium hydroxide is added to increase the volatility of ammonia/ammonium. Next the liquid is introduced in a column where steam extracts this ammonia.

Table 4.5. Digestate thin fraction upgrading technologies

Technology	Energy use	Unit	E= electricity H = heat	Source
Reversed Osmosis	0.0756	MJ/kg	E	
Ammonia Stripping	0.0252	MJ/kg	E	
	0.324	MJ/kg	H	
Vacuum Evaporation	0.05	MJ/kg	E	
	2.57	MJ/kg	H	

4.3.7. Digestate pasteurization

To ensure all harmful bacteria and viruses are killed after AD digestion a pasteurization process is used which heats the digestate from 48 C out of the digester to 70 C before entering the digestate tank or in the case of the second digester after removal from the second digester (Table 4.5).

Table 4.6. Energy requirements for pasteurization unit

Technology	Energy use	Unit	E= electricity H = heat	Source
Pasteurization unit electricity use	0.0006	MJ/kg	E	
Pasteurization unit heat use	0.0042	MJ/kg.K	H	

4.3.8. Vehicular Fueling

The upgradation process produces gas comparable with natural gas and, therefore, can also be used as a vehicular fuel. But to inject fuel in the vehicle, it must be fed into a fueling station, from where it can be converted to CNG or LNG, to be injected inside the vehicle. The fueling station has its own compressor to compress the gas and chillers which requires electric power to be driven. Green fuel is basically compressed or liquefied methane coming from the upgrader before injection into the gas grid (Table 4.6). This compressed fuel can be used in truck and tractors in combination with diesel.

Table 4.7. Energy requirements of green gas compression system for use as green fuel

Technology	Energy use	Unit	E= electricity H = heat	Source
Atlas Copco compression unit	0.1839	MJ/Nm3	E	

4.3.9. Green gas as transport fuel

Using green gas as a transport fuel is advantageous as they can reduce emissions drastically. Companies like *Scania* and *Volvo* have developed trucks which run on upgraded biogas. This makes biogas transport attractive and hence looking into such an option would add another dimension to the utility of the gas. The fuel consumption of such a truck with a load carrying capacity of 26 tonnes was obtained from Scania and it was claimed to be 23.4 kg/100km under a cruising speed of 85 km/hr. While that of a conventional diesel truck was given as 27.7 litres/100km at the same speed. Biogas as fuel can also be used for tractors. *Valtra*, *New Holland*, and *Steyr* are some of the manufactures exploring this option. Hence, for transportation only trucks were considered. Each and every technology has its own implication on the environment. In order to combine them and evaluate their collective effect, a methodology has to be framed. This has been described in the next part. For transport within the BioGas simulator diesel truck transport is utilized. A big impact of transport can be replaced by using green gas as a fuel, however, the construction, maintenance, construction and maintenance of the road, and the use of lubricant and or other materials cannot be replaced. Therefore, 50% of the energy use of transport will be replaced by green fuel and the rest will still have an impact (Table 4.7).

Table 4.8. Fuel consumption of different types and ages of trucks

Technology	Energy use	Unit	Source
Green gas truck new	0.23	kg/km	
	0.479	MJ/Ton.km	
Diesel truck new	0.277	L/km	
	0.381	MJ/Ton.km	
Energy use truck average NL	1.31	MJ/Ton.km	FTN/BECO Groep

* Based on a 26 Ton load capacity of the truck
* Green fuel is 54.2 MJ/kg
* Diesel is 35.8 MJ/L

5. STEP 3: BIOMASS AVAILABILITY

The AD system is located on a dairy farm in the middle of the biomass collection area, represented as a circle (biomass circle). The distribution of biomass, dairy farms, and agricultural farms, averaged for the Netherlands, are retrieved from Pierie, et al., [33]. In addition, catch crops (e.g. flower rich margins or buffer strips) are also used as feedstock for the AD system. During the cultivation of catch crops the use of machinery and fossil fuel is taken into account for seeding and harvesting, no fossil fertilizers are used. Average biogas and methane yield values are selected resulting from several combinations of catch crops [34]. The radius of the biomass circle is determined by the feedstock needs of the AD system; therefore, the mix of feedstocks is determined from the availability of biomass in the biomass circle (Table 5.1). With the average radius of the biomass circle known the average transport distances can be determined [2]. Additionally, a tortuosity factor is included, which represents inefficiencies in transport (e.g. winding roads, multiple pickup locations), [2, 35], (Table 5.1). A clear description of the aforementioned can be found in in Pierie, et al., [33]. For biomass waste flows only transport cost are included (Table 5.1), except for manure from external sources where negative prices are used within the Netherlands, due to its over-abundance [14], and for roadside grass where harvesting costs from road embankments are included [36].

Table 5.1. Feedstocks used including costs and transport retrieved from Pierie et al. [2, 3]

	Feedstock Mg/a	Costs €/Mg	Tortuosity factor	Transport km	Biogas potential Nm3/Mg.oDM[a]	Methane potential Nm3/Mg.oDM[a]
Manure farm/cooperation	1820	0	1	0.1[d]	350	180
Manure source	8000	-10[b]	1.5	1.5	350	180
Chicken manure	475	0	1.5	3	416	212
Natural grasses	6000	10[c]	5	15	560	297
Tops sugar beets	1100	0	1.5	3	550	302
Tops potatoes	2300	0	1.5	3	550	302
Straw from grains	500	0	1.5	3	341	174
Catch crops	1100	0	1.5	3	640	329
Digestate	-	-	-	-	47[f]	19[f]
Energy Maize (Reference)	10000	35[e]	1	50	606	322

[a] Biogas and methane potential in production per Mg of organic Dry Matter
[b] Price of manure from external sources derived from and Kwin, 2013 [14]
[c] Price of grass from road embankments and natural areas [36]
[d] Transport by pipeline
[e] Costs of maize feedstocks derived from Kwin, 2013 [14]
[f] Biogas and methane potential of the digestate retrieved from [37]

The farmers interviewed indicated the availability of the aforementioned biomass sources, however, they stressed the argument that removal of carbon and structure from the field must be done with care; this is mostly for both potato and beet tops and catch crops. Also, currently straw has very good value in the market and, therefore, there are now surpluses available and cost prices will be substantial. For chicken manure the quality issue of the manure was raised, as it can contain pollutants unwanted in the digestate. Within this context, additional sources of biomass from road embankments or natural areas are also debated as the quality is often low. Often, roadside grass and natural grass is left to dry for an extended period, which removes a lot of the biogas potential; this is done to make transport more efficient. Instead, autumn grass from permanent grasslands is proposed as alternative; or remains from ditches containing duckweed and other aquatic plants. In the latter source, quality will again play an important role as the biomass can contain pollutants. Lastly, all biomass indicated for use already has an owner which most of the times also already has a use (or buyer) for the biomass, which will need to change if the biomass will have another use. Within the agro sector there in only a little real waste. One possible example can be road side grass. However, quality is often low and collecting fresh grass will cost more, also requiring significant adaptation in the maintenance fleet.

6. STEP 4: PLANET (BioGas Simulator)

The Environmental impact assessment is based on previous research of a theoretical case study [38], a master thesis performed with in the project (Source), and the kitchen table discussions performed within the Agro-Cycle project. The results from the three methods are combined and used to update the BioGas simulator with up to date values.

6.1. Reference AD system

All scenarios will use the same AD plant setup as a starting point (See section 4.1), (Fig. 6.1). When comparing the reference case of a linear biogas production pathway (Fig. 6.1.) using the local biomass availability (Section 5) the possible reduction is minimal. Overall the combined heat and power scenario (REF CHP) performs best in regard to the efficiency and environmental indicators as it is able to utilize most of the energy in the biogas in the shape of electricity and heat (Fig. 6.2). Unfortunately, in reality this is not often the case as only the required heat in the process can be utilized where the rest is lost. When only looking to electricity production using heat for your own process (REF P) reduction in environmental impact is minimal.

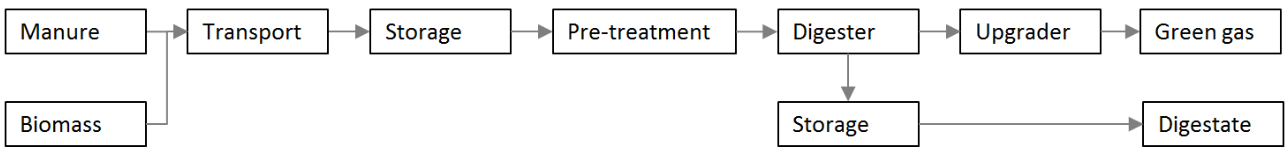


Fig. 6.1. Main green gas production pathway of the Normal scenario

The green gas production pathway (REF CNG) only has a minor reduction in emissions and impact with a low efficiency. The low efficiency is caused by the use of electricity from the national grid, whereas in the CHP scenarios electricity is produced internally. The basic economic analysis indicates a negative NPV for all cases over 35 years (Fig. 6.2d), with the green gas scenario making the smallest loss as it can sell the most amount of high quality energy in the shape of green gas. Overall, regarding only minimal use of waste heat, possible reductions are not substantial as for emissions only around 40% can be reduced and for environmental impact only around 15% can be reduced compared to natural gas. For the business case the NPV over 25 years is negative, indicating that selling only energy as green gas electricity or heat will not suffice. Within the context aforementioned, new business cases will need to be developed based on a more efficient and even circular system.

Scenario	Description
Natural gas:	Groninger natural gas
REF CNG:	Production of compressed green gas using biogas
REF CHP:	Production of combined heat and power using biogas with all heat used
REF P:	Production of combined heat and power using biogas with only process heat used

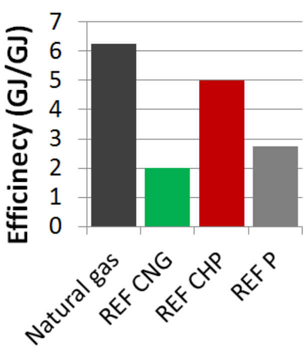


Fig. 6.2a. Efficiency

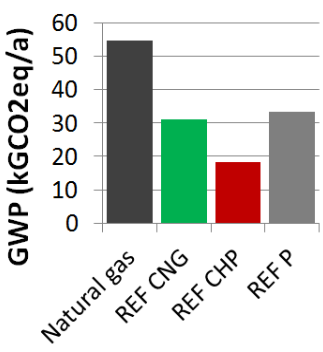


Fig. 6.2b. Emissions

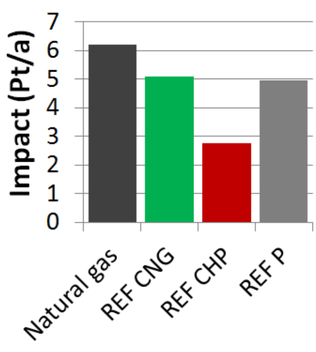


Fig. 6.2c. Impact

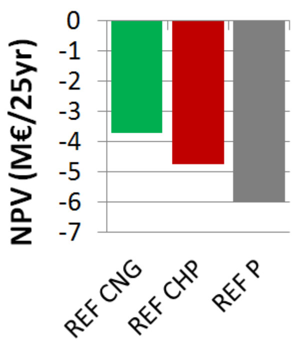


Fig. 6.2d. Net Present Value

6.2. Environmental impacts upgrading biogas and digestate

Within this chapter an assessment is made of the environmental impact of several biogas upgrading technologies to green gas and digestate processing technologies to green fertilizer.

6.2.1. Results part I - Individual Cases

The individual technologies were modelled after the available biomass and its subsequent mass flow; the energy requirements of the digester and filtration systems are assumed constant (Ref case). The energy requirement of the complete system will be fulfilled with a CHP unit. No other source of energy is used either internally or externally for energy requirements. The losses were also considered while modelling. Excess of heat and electric power was counted as waste energy. The results here show the individual effect of each technology with the same biomass, digester, and filtration unit. The results are shown in the form of a bar-chart showing all the three impact indicators. The scales used in the figures to indicate results are elaborated in table 6.1.

Table 6.1. Expressions in figures section 6.2

Expression	Unit	Axes used
Process Energy Returned on Invested (P)EROI	GJ/GJ	Left axes
Global Warming Potential 100 year (GWP)	kgCO2/GJ	Left axes
EcoPoints (Pt)	Pt/GJ	Left axes
Green gas injected	Nm3/a	Right axes

The Upgradation Technologies: The 5 upgrading technologies have different effects on the result. Water scrubbing has the highest efficiency and lowest load on the environment, while the Global Warming Potential (GWP) of cryogenic separation was the lowest. The better performance can be associated with the fact that water scrubbing uses moderate amount of energy compared to others which means less biogas is used as fuel in the CHP unit. It could be estimated that this trend will also continue to impact the result of the symbiotic scenarios, as using amine scrubbing will increase the overall energy of the whole system and thereby will curb its efficiency and increase its emissions. The amount of injected green gas as a replacement for natural gas will also decline in amine scrubbing cases. However, amine scrubbing has a better efficiency and fewer losses, which could be a factor in the symbiotic cases.

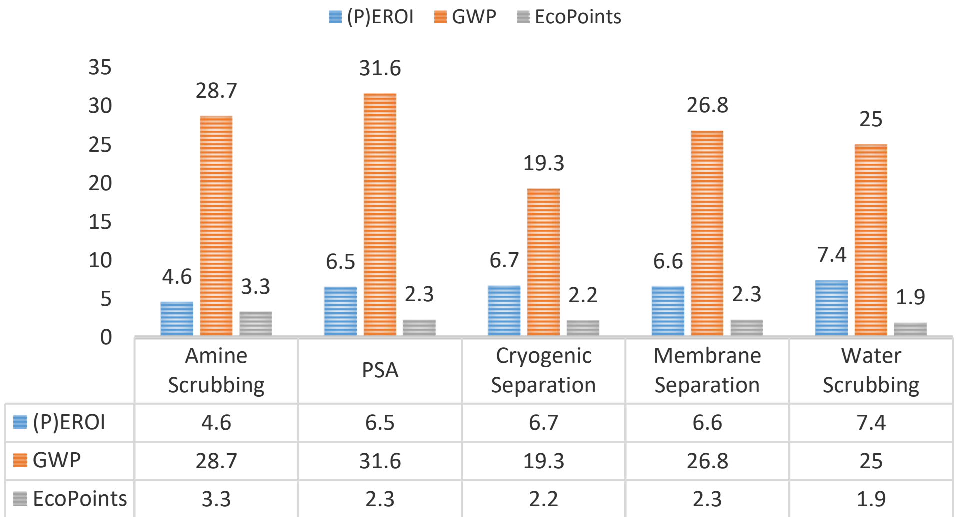
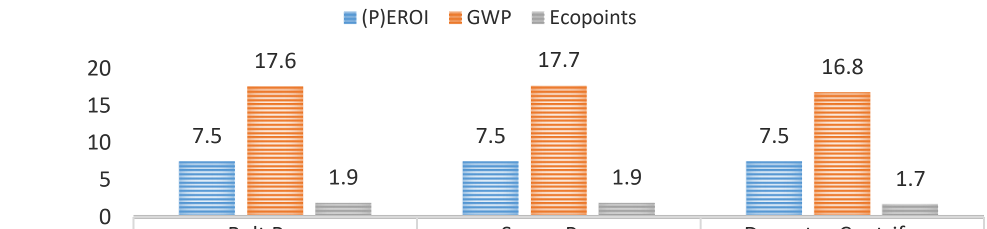


Fig. 6.4. Graph for upgrading technologies

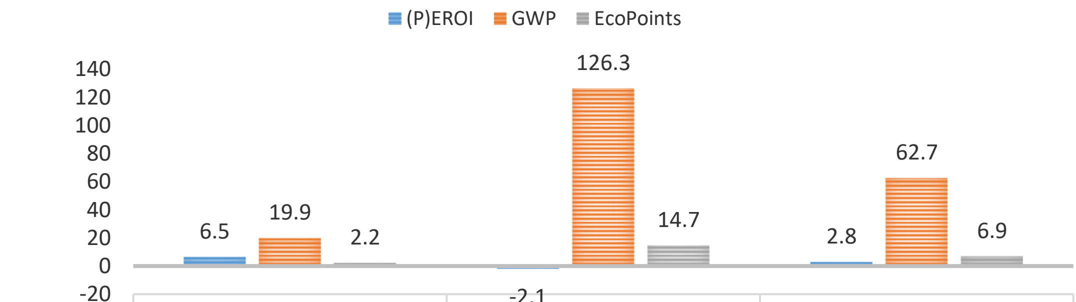
Digestate Separation: All the digestate separation techniques are found to be equally efficient with very minor changes (fig. 6.5) and require the same size of CHP unit. A decanter centrifuge has a greater energy consumption and in this case the utilization of energy from the CHP unit is high. However, in a symbiotic scenario this can change as the decanter centrifuge will increase the system's energy requirements, which can cascade to greater emissions, environmental impact, and less green gas to grid.



	Belt Press	Screw Press	Decanter Centrifuge
(P)EROI	7.5	7.5	7.5
GWP	17.6	17.7	16.8
Ecopoints	1.9	1.9	1.7

Fig. 6.5. Graph for digestate separation

Ultra-Separation: There are three technologies included for ultra-separation of the thin fraction, namely; reversed osmosis, vacuum evaporation, and ammonia stripping. Vacuum evaporation requires a substantial amount of energy as heat resulting in a negative (P)EROI, which has further negative impact on the GWP as well as the EcoPoints. It is very unlikely, that even in symbiotic scenario vacuum evaporation process will provide any positive influence as its energy requirements are substantially higher that the other processes. Reverse Osmosis is the most promising case with balanced impacts.



	Reverse Osomosis	Vacuum Evaporation	Ammonia Stripping
(P)EROI	6.5	-2.1	2.8
GWP	19.9	126.3	62.7
EcoPoints	2.2	14.7	6.9

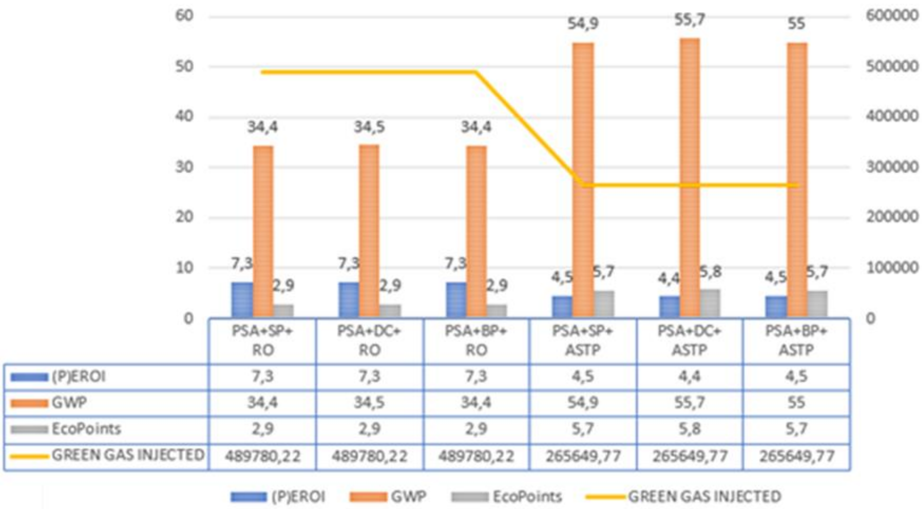
Fig. 6.6. Graph for ultra-separation of digestate

6.2.2. Results part-II Symbiotic Scenarios

In the symbiotic scenarios each upgradation technology was taken as a base scenario and then combined with separation and ultra-separation options. The energy consumption for refueling station (in case a part of gas is used for vehicle fuel) was also included. The CHP units were adjusted to the process energy needs. The energy balance was maintained in a way that neither the heat nor the electrical energy of the system would need any other means to fulfil the requirement (e.g. electricity or natural gas from the national grid). So, if the difference between heat and electrical energy requirement of the system and the heat and electrical energy provided by the CHP are "0" in respective cases or least negative value, then that CHP is accepted in the system. CHPs having higher ratings will cause wastage of energy (electricity can be injected to grid, but heat gets dissipated to the surroundings) and consume more biogas, thereby, decreasing the injection of green-gas to the gas grid. Within the scenarios excess heat is treated as waste, whereas, excess electricity is counted as useful energy placed on the national grid. The results of symbiotic scenarios have been shown through the graphical representations below. They have been divided according to the Upgradation technology as stated above.

Symbiotic scenarios with Pressure Swing Adsorption: PSA in combination with RO showed promising results. While the (P)EROI increased in comparison to the individual case the global warming potential increased too. The EcoPoints however remained almost identical. The green-gas injected into the grid was

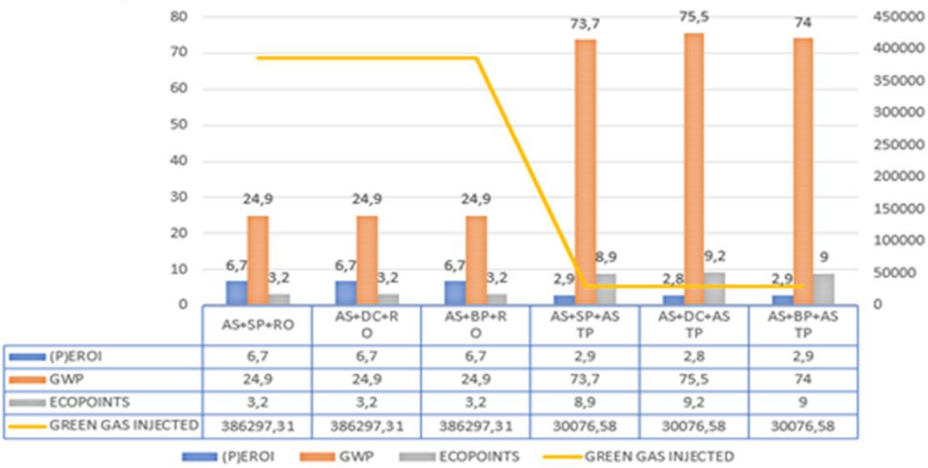
489780.22Nm^3/annum. The increase in (P)EROI can be explained by the fact that better utilization of power was achieved with a small CHP engine. But, increase in GWP potential is since more biogas is being used as fuel compared to the individual case. The EcoPoints remain almost identical stating the fact that the combination with RO has a very low effect on the environment and is beneficial. But, the other side of the graph indicates lower performance. With AS technique the (P)EROI gets reduced to almost 50% of the RO scenario, while the GWP and EcoPoints get significantly higher. The CHP unit used is bigger than the previous cases. The bigger engine consumed more biogas, so green gas available for injection in the grid was 265649.77Nm^3/annum.



	PSA+SP+RO	PSA+DC+RO	PSA+BP+RO	PSA+SP+ASTP	PSA+DC+ASTP	PSA+BP+ASTP
(P)EROI	7,3	7,3	7,3	4,5	4,4	4,5
GWP	34,4	34,5	34,4	54,9	55,7	55
EcoPoints	2,9	2,9	2,9	5,7	5,8	5,7
GREEN GAS INJECTED	489780,22	489780,22	489780,22	265649,77	265649,77	265649,77

Fig. 6.7. Graph for symbiotic scenarios with PSA

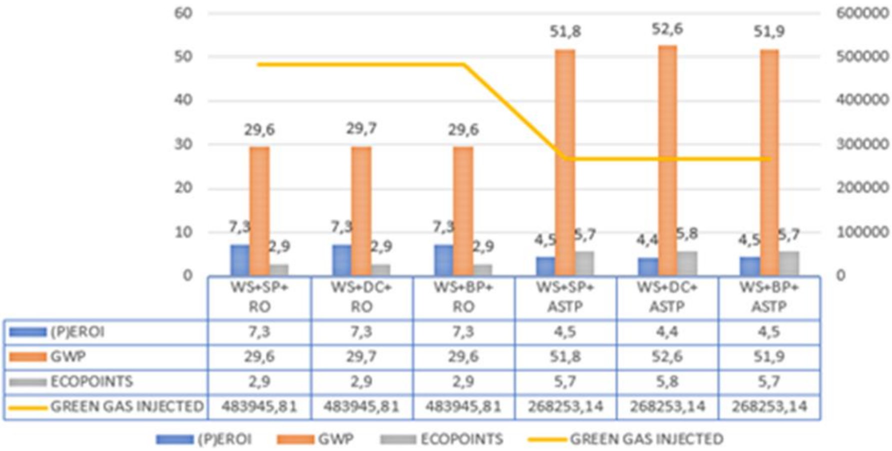
Symbiotic scenarios with Amine Scrubbing: AS scenarios reflected the same trend as in previous case. AS and ammonia stripping both require heat energy, thereby collectively increasing its demand in the whole process. Since heat required is more the CHP size also increases for both reverse osmosis and ammonia stripping as compared to PSA cases. AS and ammonia stripping cases consecutively inject only 30076.58 Nm^3/annum of green gas in the grid. The CHP unit used is the biggest of all the cases as shown in Appendix. In the RO cases for AS, less heat was wasted and more electricity was injected in the power grid as compared to PSA. Thus, even though (P)EROI is decreased slightly, the GWP also remains low. The green gas injected into the grid also lowers to 386397.31 Nm^3/annum. Overall, the graph clearly indicates the processes with higher energy requirement cause greater impact and less productivity. The RO cases are more favorable than the ammonia stripping cases. This is mainly because of the energy consumption of the ammonia stripping cases and high amount of heat energy which is left unutilized. Also, due to the CHP a very low amount of green gas is injected into the grid. The difference in green gas injection is the highest.



	AS+SP+RO	AS+DC+RO	AS+BP+RO	AS+SP+ASTP	AS+DC+ASTP	AS+BP+ASTP
(P)EROI	6,7	6,7	6,7	2,9	2,8	2,9
GWP	24,9	24,9	24,9	73,7	75,5	74
ECOPOINTS	3,2	3,2	3,2	8,9	9,2	9
GREEN GAS INJECTED	386297,31	386297,31	386297,31	30076,58	30076,58	30076,58

Fig. 6.8. Graph for Symbiotic Scenarios with AS

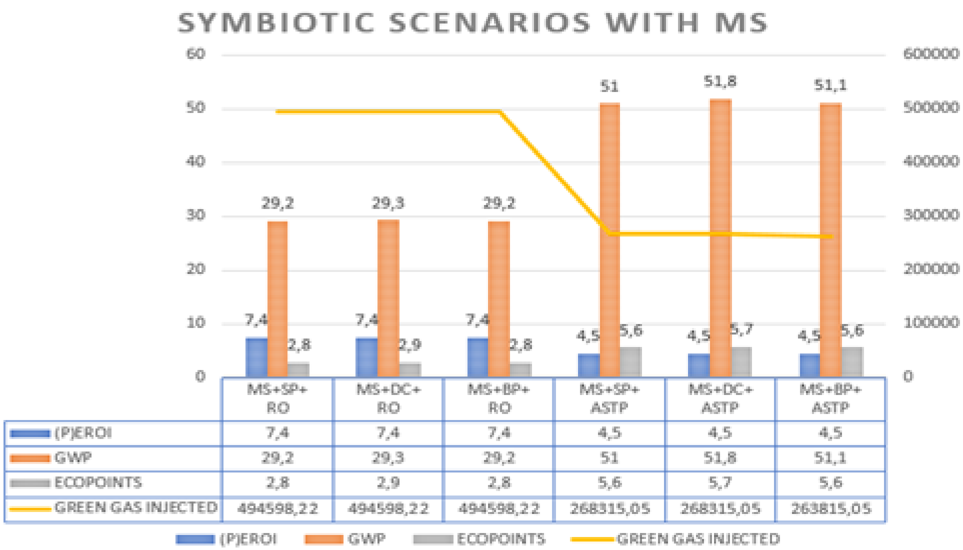
Symbiotic scenarios with Water Scrubbing: As Water Scrubbing has slightly more electrical consumption than that of PSA, the outputs were also in the same range. However, the CHP engines were bigger, for RO it was 100kWe (Veolia) engine and for ammonia stripping it was 205kWe (Ener-G). Green gas injection was also decent when compared to PSA. The ammonia stripping part of both PSA and WS is associated with the same unit of CHP. But, a difference of green gas injection was observed, and it was found that WS injects more green gas than PSA for the same CHP unit. This was mainly because loss of biogas in WS is less than loss in PSA (table). The result displayed in the graph illustrates it further.



	WS+SP+ RO	WS+DC+ RO	WS+BP+ RO	WS+SP+ ASTP	WS+DC+ ASTP	WS+BP+ ASTP
(P)EROI	7,3	7,3	7,3	4,5	4,4	4,5
GWP	29,6	29,7	29,6	51,8	52,6	51,9
ECOPOINTS	2,9	2,9	2,9	5,7	5,8	5,7
GREEN GAS INJECTED	483945,81	483945,81	483945,81	268253,14	268253,14	268253,14

Fig. 6.9. Graph for symbiotic scenarios with WS

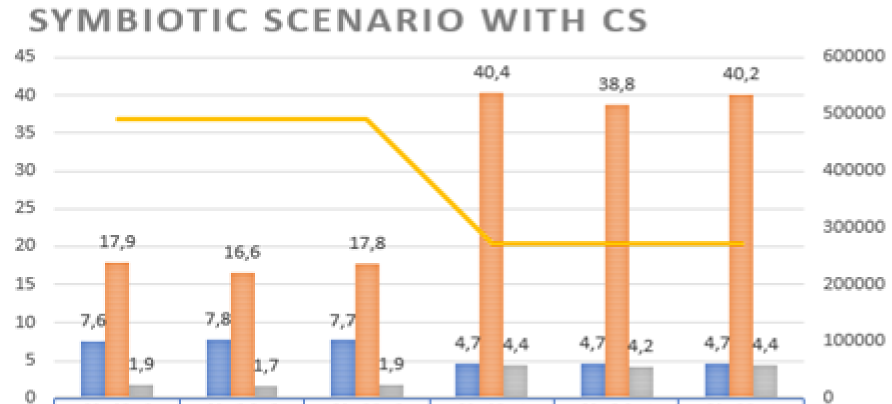
Symbiotic scenarios with Membrane Separation: Membrane separation used 81kWe (Ener-G) for RO and 205kWe (Ener-G) for ammonia stripping. It was like PSA, WS in terms of results of the impact indicators while green gas injection differed. The reason behind having a different green gas injection can be explained in the following ways. Compared to PSA, MS has better performance efficiency and fewer losses. This means it retains more gas. So, in RO cases it has higher injection of green gas, but in ammonia stripping cases this decreases as the CHP of PSA is a smaller unit. When compared to WS, in RO cases MS uses a smaller engine and hence greater output. But, interestingly in ammonia stripping gas injected to the gas grid is more in MS than in WS although they have identical losses and use the same CHP engine. This is a result of the efficiency difference between the two technologies. As shown in table MS is less efficient than WS. This indicates more trace gases can be found in MS systems than in the WS system. This leads to the greater amount of green gas in the gas grid, but this also means that methane content will be a little lower.



	MS+SP+ RO	MS+DC+ RO	MS+BP+ RO	MS+SP+ ASTP	MS+DC+ ASTP	MS+BP+ ASTP
(P)EROI	7,4	7,4	7,4	4,5	4,5	4,5
GWP	29,2	29,3	29,2	51	51,8	51,1
ECOPOINTS	2,8	2,9	2,8	5,6	5,7	5,6
GREEN GAS INJECTED	494598,22	494598,22	494598,22	268315,05	268315,05	263815,05

Fig. 6.10. Graph for Symbiotic scenarios with MS

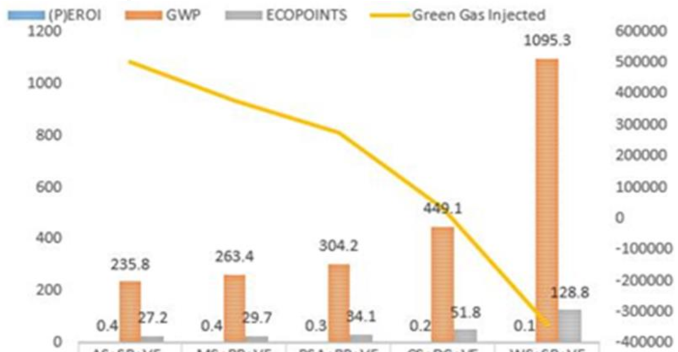
Symbiotic scenarios with Cryogenic Separation: The last of the scenarios involved CS. The RO cases were more favorable than the ammonia stripping as in earlier cases. The green gas injection was more in CS cases for RO in spite of using a bigger CHP engine compared to PSA and MS, same as that of WS is because the CS has a lower loss of 0.5% of methane. For RO cases it uses 100kWe CHP (Veolia) as its energy intensive and for ammonia stripping it uses 205kWe CHP (Ener-G).



	CS+SP+RO	CS+DC+RO	CS+BP+RO	CS+SP+ASTP	CS+DC+ASTP	CS+BP+ASTP
(P)EROI	7,6	7,8	7,7	4,7	4,7	4,7
GWP	17,9	16,6	17,8	40,4	38,8	40,2
ECOPOINTS	1,9	1,7	1,9	4,4	4,2	4,4
GREEN GAS INJECTED	491793,87	491793,87	491793,87	272683,6	272683,6	272683,6

Fig. 6.11. Graph for symbiotic scenarios with CS

Symbiotic scenarios with Vacuum Evaporation: Lastly, there is the curious case of using vacuum evaporation which has high energy requirements especially heat. No CHP unit was able to provide the enormous amount of heat required. So, as predicted earlier from the individual cases that this is an energy draining process. The results have been recorded in Appendix. To take a further look in the system behavior the symbiotic scenarios involving VE they were first clubbed with a 64kWe (Veolia) engine and then 5 random cases were clubbed with various other engines of higher capacities to know the behavior of the symbiotic scenarios. Clearly the impact was huge and the industrial symbiosis was not achieved as the energy requirement was way beyond the scope of the CHP engine. Thereby, VE cases were discarded as a possibility. The graph below shows the special cases. It clearly illustrates the above statements.



	AS+SP+VE 81kWe	MS+BP+VE 150kWe	PSA+BP+VE 205kWe	CS+DC+VE 309kWe	WS+SP+VE 550 kWe
(P)EROI	0.4	0.4	0.3	0.2	0.1
GWP	235.8	263.4	304.2	449.1	1095.3
ECOPOINTS	27.2	29.7	34.1	51.8	128.8
Green Gas Injected	502336.04	380305.95	276694.14	30086.35	-341759.74

Fig. 6.12. Graph for selective VE cases with different CHP units

6.3. Case study for AD within agriculture

The symbiotic AD system case is based on a cooperation of five dairy and seven agricultural farms, which are treated in this article as a single entity called the cooperation, combined with the knowledge gained from the analysis of several technologies for using and upgrading biogas. The required amount of farms within the cooperation is determined by the feedstock needs of the AD system (Table 6.1). The feedstocks acquired within the cooperation (including manure) only include transport costs. Within the theoretical case all manure is retrieved within the cooperation. The cooperation will use biomass from the local government and water board responsible for managing the biomass growth alongside roads, canals, natural areas, and/or parks (Table 6.2); however, this will include harvesting costs (Table 6.2). The fields used for roadside grass and natural grasslands do not require fertilization, due to natural inflow of nutrients. Regulation regarding green gas production within the Netherlands is stable with a guaranteed subsidy for a maximum of 22 years, however, the taxes and subsidy schemes for the symbiotic systems aforementioned are currently undefined; therefore, the effect on the yearly costs is difficult to indicate. For instance, policies and subsidies for green electricity, green gas and green fuel produced and used within the cooperation are currently nonexistent. Within the NPV cost calculation the Dutch low tax rate of 6% (in 2018) is included for the internal energy products produced within the cooperation (e.g. electricity, green gas, green fuel, and green fertilizers), which is comparable to the current form of subsidy.

Table 6.2. Energy and fertilizer requirements cooperation of farms

	Unit	Dairy farms	Agricultural farms	Natural areas	Total	Source
Average farms needed	farms	5.4	6.9		12.3	
Agricultural land size	ha	270[a]	276[b]	275[c]	821	[14], [3]
Diesel use	l/a	35100	65688		100788	[14]
Electricity use	kWh/a	253800	151524		405324	[14]
Natural gas use	Nm3/a	8640	2898		11538	[14]
Nitrate cap[d]	Kg/a	71550	46920		118470	[14]
Phosphate cap[d]	Kg/a	25650	17940		43590	[14]
Potassium cap[d]	Kg/a	60750	62100		122850	[14]

[a] Based on average dairy farm with 100 cows and two cows per hectare of land [14]

[b] Based on production of beat tops, Potato tops, Straw, and Catch crops respectively 40, 20, 41, and 18.5 Mg/ha.a [3]

[c] Based on the production of roadside and natural grass of 21.8 Mg/ha.a [3]

[d] Cap means the maximum yearly allowed use of nutrients on a farm

6.3.1. Scenarios

All three theoretical cases (Table 6.3) are based on the same energy and fertilizer needs of the cooperation (Table 6.2). The cases (Table 6.3) are based on the average land occupation and feedstock availability described.

Table 6.3. Main cooperative farming cases

affiliation	Description of the sustainable farming cooperation cases
REF (Case)	**The reference cooperation (REF):** In this case, based on current average farming activities in the Netherlands, the cooperation will import all of their energy and most of their fossil fertilizers. The dairy farms within the cooperation will use their own manure as fertilizer on their fields, whereas agricultural farms will use fossil fertilizer for all their nutrient demands. Additionally, fuel for the machinery, electricity, and natural gas are imported to supply the energy needs of the cooperation. The environmental impacts of fertilizer, fuel, electricity, and natural gas production are included. Inflation and increase of prices for energy and fertilizers are taken into account for the upcoming 25 years.
AD (Case)	**The AD cooperation (AD):** Within this case, the cooperation will operate a circular symbiotic AD system, producing renewable energy and fertilizer from local bio-waste. Dairy farmers within the cooperation use the digestate from the AD system as fertilizer on their fields. Excess digestate is processed into green fertilizers and used by agricultural farms in the cooperation. Additionally, the fuel for the machinery, electricity, and natural gas is supplied by the AD system (Table 4). The remaining energy or fertilizer requirements are imported. The overall cost of the AD system is based on the NPV calculation. Within this case 23% of the total digestate output is upgraded into green fertilizer to replace fossil fertilizer. The income from selling the remaining green gas is incorporated in the NPV; however, mitigation of carbon footprint and environmental impact by replacing green gas with natural gas is not included, as it does not lower the impacts of farming practices itself.
AD+M (Case)	**The AD cooperation using surplus manure (AD+M):** The AD+M case is similar to the AD case, except, within this case a surplus of manure from surrounding dairy, pig, or chicken farms of 10,000 Mg is available for the production of additional energy and green fertilizer. In some parts of the Netherlands there is a surplus of manure available, often linked to farms with no agricultural land (e.g. pig, chicken farms). For the additional manure feedstock mixture the properties of cow manure are assumed. Within this scenario around 50% of the total digestate output is available for upgrading to green fertilizer, which can be used to replace fossil fertilizer. Excess fertilizer is sold on the market for market prices.

The cooperative case is based on individual improvement options (fig. 6.13): these can be combined in a symbiotic AD system to improve the indicators of sustainability (e.g. Planet, Profit). Within the BioGas Simulator individual technologies can be switched on or off to come to the most optimal symbiotic scenario focused on one or multiple indicators of sustainability.

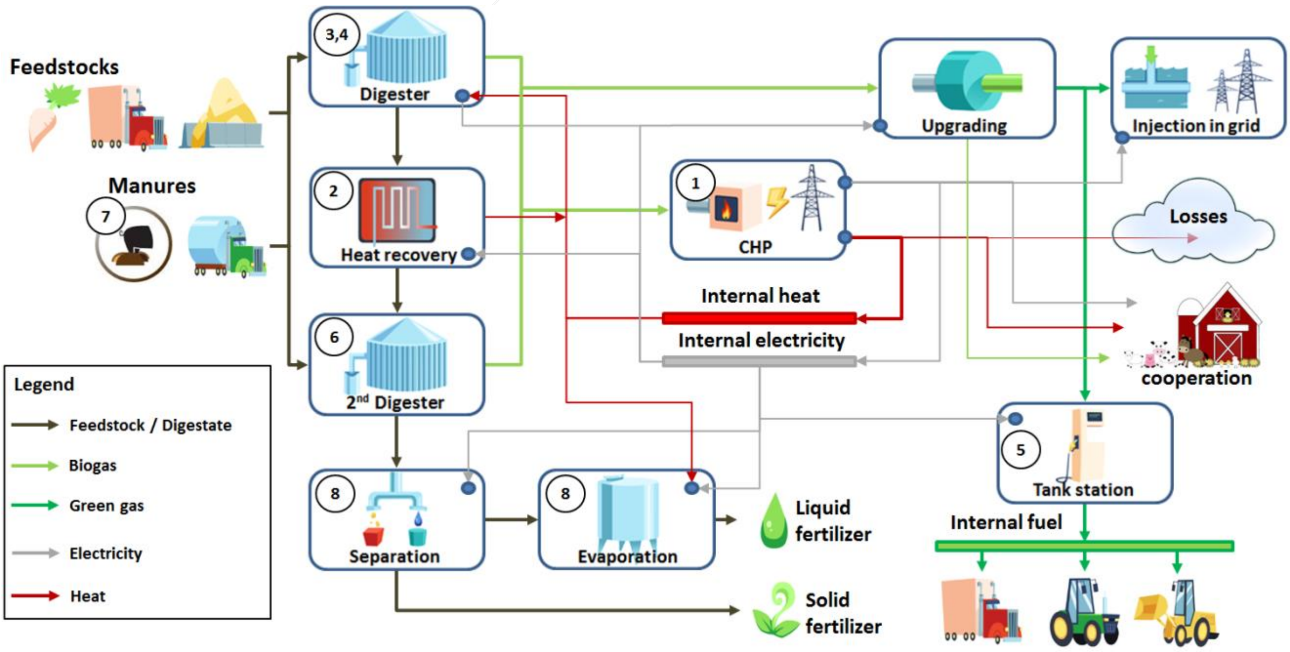


Fig. 6.13. The optimized AD system for use in the sustainable farming concept

Table 6.4. Main improvement options

Nr.	affiliation	Description of improvement option
1)	CHP	A Combined Heat and Power unit (CHP) is used to produce electricity and heat [3] to fulfil the energy demand of the complete AD system (e.g. digester, green gas production, digestate upgrading). Cables and pipelines are incorporated for transportation to the AD production processes [3]. Additional heat requirement not supplied by the CHP is produced by the biogas boiler. In the case of overproduction electricity is put on the local electricity grid and heat is discarded.
2)	Recovery	The main digester operates at a mesophilic temperature of around 35 to 48 degrees Celsius; outgoing digestate will be at the same temperature. Therefore, heat energy in the outgoing digestate can be utilized through a heat exchanger to heat up the ingoing feedstocks at ambient temperature fed into the digester. Infrastructure and energy use for heat recovery is taken into account (Appendix Table 3).
2)	Heat pump	Additionally a heat pump can be added to the Heat recovery system aforementioned to more effectively produce heat with an average COP of 3 to 4.
3)	Insulation	Insulation of the main digester will lower the heat loss from the main digestion tank, which operates at mesophilic temperatures. Therefore, biogas can be saved resulting in more green gas finally produced. Insulation will bring with it additional capital expenditure and embodied energy but will also reduce the heat demand of the process. Heat requirement of the main digester is lowered with 20% to simulate the effect of insulation on the SI-Indicators.
4)	Prevention	Gas leakages can be prevented through the use of repair and higher greenhouse gas emissions (e.g. methane) can be reduced using catalytic conversion lowering the carbon footprint. Repair focusses on actual leaks in biogas equipment such as the main and second digester, piping, upgrading installations. Catalytic conversion focusses on outputs from upgrading or combustion, which often contain methane or Nitrogen oxides, which are brought back to $CO2$ level using catalytic conversion. Within this improvement option, losses and emissions from the main digester and second digester are eliminated and higher greenhouse gas emissions from the green gas utilization pathway and CHP unit are reduced to carbon dioxide level.
5)	Green fuel	Green gas produced by the AD plant is used as fuel for agricultural machinery ranging from tractors, front loaders, and trucks transporting the biomass, replacing the use of fossil fuels (e.g. diesel). To achieve the aforementioned, infrastructure in the shape of a filling station is needed [39] which compresses the green gas and stores it in large enough quantities to fill several tanks (Appendix Table 3).
6)	2^{nd} digester	Processed digestate still contains some biogas potential [37]. However, it is often not efficient and economical to retain this using the main digester, as it is kept at mesophilic temperature and is stirred continuously. Within this context, a second digester (not heated and often stirred) can be used to store the digestate and collect the residual biogas production. The longer retention time in the second digester (up to 5 to 6 months) gives the AD process additional time to break down the last remaining digestible organic material into biogas. Infrastructure and energy use is taken into account (Appendix Table 4), also including the biogas potential of digestate which is based on an average number, as digestate composition is dependent on the feedstocks use in the digester (Appendix Table 4).
7)	+Manure	Due to overabundance and low quality, the available manure is often not fully utilized. Manure can be directly pumped in the second digester to retain the produced biogas to replacing seasonal manure storage during winter or mix it with the digestate for utilization in fertilizer production. This technology can also produce additional environmental benefits, which can be mitigated. A maximum of 10000 Mg of additional manure is added directly to the second digester. Infrastructure and energy use is taken into account (Appendix Table 4). For determining the biogas production of the additional manure the biogas potential of manure is used (Table 1).
8)	Green fertilizers	Within this improvement option, a large share of the digestate (80%) is separated into a thick and a thin fraction using a manure separator [40]. The thin fraction is rich in nitrogen and contains most of the water, whereas the thick fraction contains most of the phosphates, potassium and organic materials. The thin fraction is processed using reversed osmosis to decrease the water fraction [41, 42]. The processed and upgraded thin and thick fractions are used as green fertilizers on the farm replacing fossil fertilizers (table 5). The remaining 20% of the digestate is used for replacing manure fertilization on the pasture; however, this will not replace fossil fertilizers. The needed infrastructure and energy use of the installations is taken into account.
8)	Selling fertilizers	Green fertilizers can also be sold on the market when own demand is fulfilled, unfortunately for lower prices. Within this improvement option all the green fertilizer produced is sold on the market (Appendix Table 3).

6.3.2. Results

The results from the technical analysis are brought together in a single technological design containing AD, with Membrane upgrading, a reciprocating CHP, screw separation of digestate and reversed osmosis used for upgrading the thin fraction. Transport fuel is replaced by green gas also including the diesel requirements of the cooperation of farms. Additionally, the electricity and gas demand of the cooperation of farms is also supplied by the biogas installation. Without an additional input of manure above the obligated 50% in the total feedstock fertilizer demands are not completely met by own digestate; therefore, additional fossil fertilizers are required. By utilizing an AD green gas system farms within the cooperation are capable of reducing their energy demand with almost 80%, emissions with 75%, and environmental impact with 70%; which is a significant reduction (Fig. 6.14).

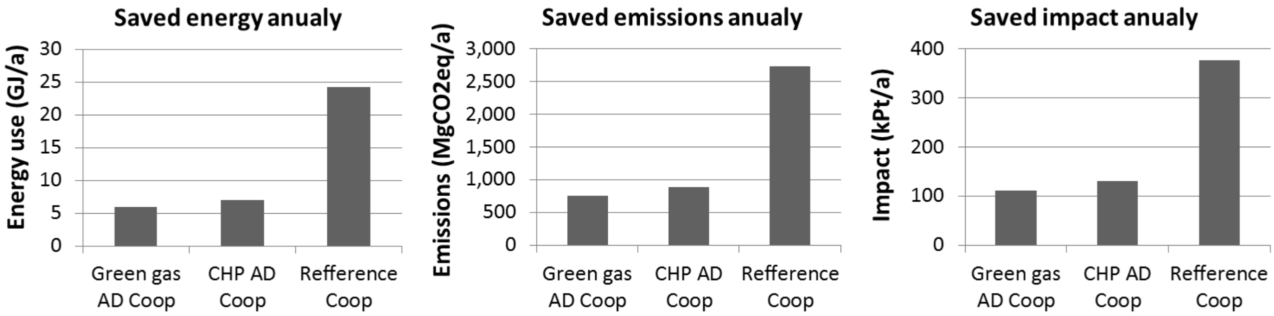


Fig. 6.14. Results of the symbiotic AD scenario

The impact of pasteurization of all digestate is minimal as most of the electricity and heat can be retrieved from the CHP with the heat as waste heat. The only added impacts are caused by the construction and installation of the pasteurization unit and a lower final production of green gas (Fig. 6.15).

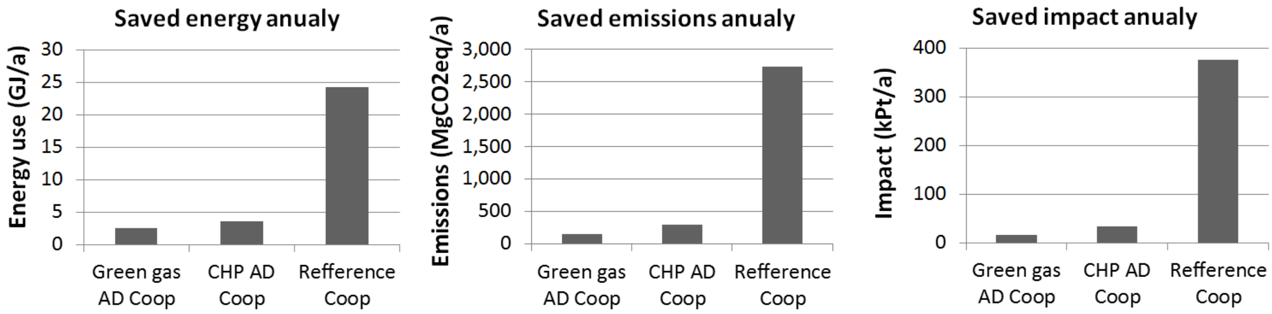


Fig. 6.15. Results of the symbiotic AD scenario including pasteurization of digestate

6.3.3. AD Symbiotic Scenarios including pasteurization of digestate

When additional manure is available, which could be from chicken or pig farms as they do not have land available, all fertilizer demands of the cooperation of farms can be filled in. As a result energy demand can be reduced with almost 90%, emissions with 95%, and environmental impact with 95% (Fig. 6.16).

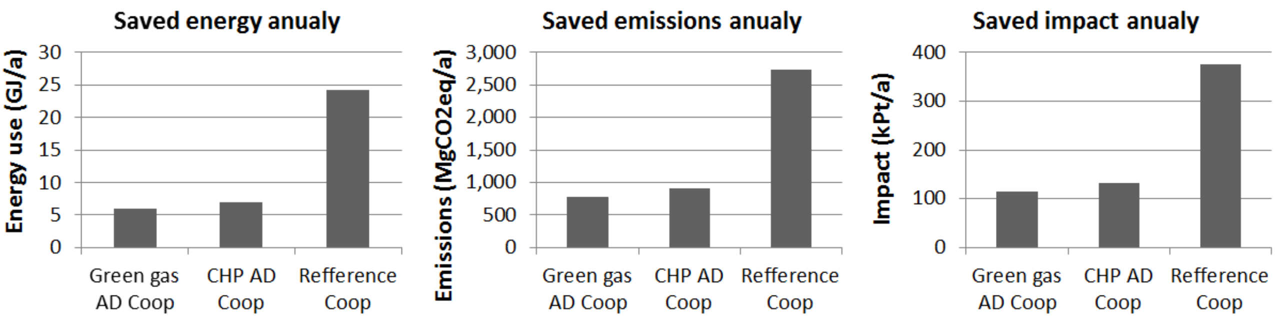


Fig. 6.16. Results of the symbiotic AD with additional manure input scenario including pasteurization of digestate

The impact of pasteurization of all digestate is minimal as most of the electricity and heat can be retrieved from the CHP with the heat as waste heat. The only added impacts are caused by the construction and installation of the pasteurization unit and a lower final production of green gas (Fig. 6.17).

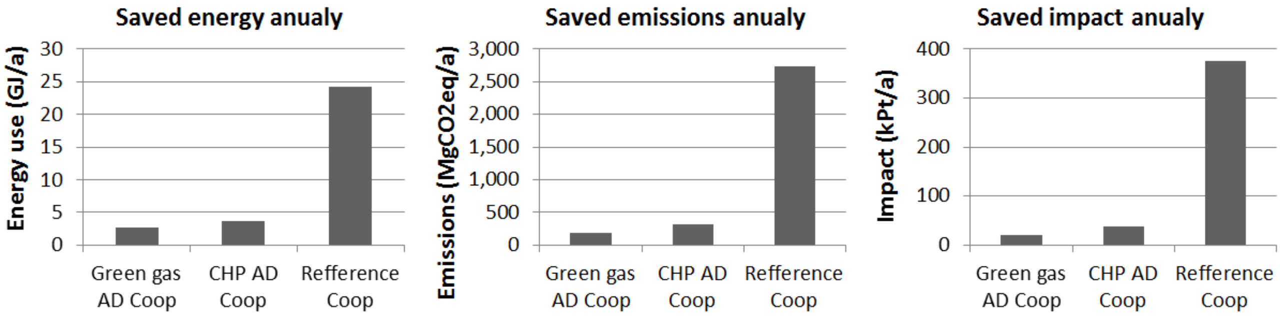


Fig. 6.17. Results of the symbiotic AD with additional manure input scenario including pasteurization of digestate

6.4. Conclusion step 4

From the environmental analysis a clear improvement regarding efficiency, emissions, and environmental impact can be observed from the results, which would support further research on the system. However, a strong link will need to be made between energy production, through the use of the cooperative AD system, and the quality of the agricultural land used as source for feedstock. A balance will need to be found between optimal land quality and renewable energy production to make the farming process sustainable. Also, the system will need to consist of multiple farms in a cooperation consisting of both animal farms (e.g. Dairy, chicken, pig) and agricultural farms (e.g. potato, sugar beets, grain, etc.), to make the system feasible. Within this context, success and also the reduction of emissions and environmental impacts is strongly dependent on the use and added value of the digestate. Therefore, when looking for reducing energy and impact of farming practices a spatial distribution of dairy, agricultural, and pig and chicken farms in close proximity working closely together within a cooperation could be suggested. Unfortunately, existing laws prevent the use of green fertilizers to replace fossil fertilizers in the Netherlands. However, without fertilizer replacement a circular symbiotic system can still be created which produces positive results for all Indicators of sustainability. Within the cooperative cases approximately half of the produced energy is used internally, the remaining green gas, electricity, and/or heat can be sold and used locally to replace fossil energy sources and help integrate other intermittent energy sources in the local energy grids. Applying the aforementioned circular symbiotic AD systems can lower environmental impact of farming by decreasing dependency on fossil based energy and fertilizers and lowering the carbon footprint from farming, helping the Dutch agricultural sector in achieving their stated environmental goals. However, to achieve the aforementioned, focused and stable policies, improved regulation, and strong cooperation must be initiated, as the regulations on green fuel and fertilizer use and subsidies for circular symbiotic systems are currently unclear within the Netherlands and European Union.

7. STEP 5: BUISINESS CASE SCENARIOS (Biogas Business Case Model)

The previous sections have focused almost exclusively CO2 reduction and the technology architecture. However, to setup and operate the above infrastructure, there should be a positive business case for all the stakeholders involved in setting up and operating the above infrastructure. Before calculating the business case a stakeholder analysis is necessary. The biogas industry is systemic in nature. Several stakeholders collaborate to produce and exploit biogas. It is important that every stakeholder involved in producing and exploiting the biogas is profitable. To conceptualize this complex interplay of stakeholders e3-value modelling technique is used. E3-value modelling technique is specifically developed to conceptualize businesses where several stakeholders collaborate to produce and exploit products and services. Such collaborations are also known as business ecosystems.

Fig. 7.1. depicts the business ecosystem that is designed to produce and exploit biogas. Two key performance indicators are vital inputs to this design namely the CO_2 emissions and profitability. The calculations in the previous section show that the system indeed reduces CO2 emissions. However, the question remains is it profitable for all the stakeholders. The following business ecosystem was designed based on the above technical model and our initial discussions with the researchers, farmers, transporter, and business consultants in the domain of the biogas industry. Next, the design was presented to the above stakeholders and refined based on their input.

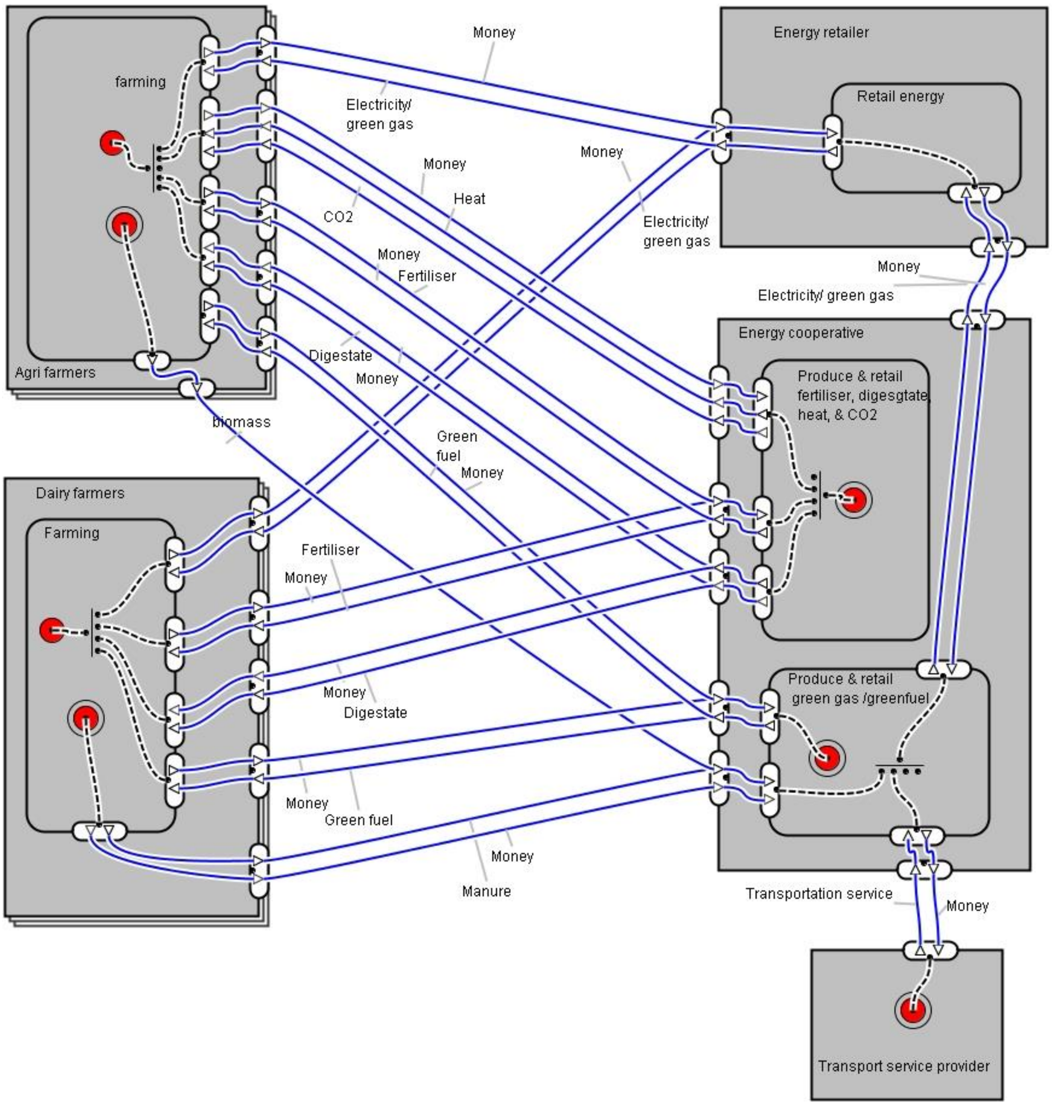


Fig. 7.1. The biogas ecosystem

Table 7.1. Stakeholder analysis

Stakeholders	Description
Energy cooperative	The energy cooperative is the central actor in the biogas business ecosystem. This actor is responsible for the setup, operation, and management of the biogas digester. The main value creation activities performed by this actor are production and retail of green gas, green fuel, organic fertilizer, digestate, heat, and CO2. All the above products are produced from the core process of anaerobic digestion and combusting biogas to produce electricity. The cooperative is formed by agriculture farmers and dairy farmers. The cooperative will hire one employee who will be responsible for the operations. The cooperatives goal is to create economies of scale and to create synergy between agriculture farmers, dairy farmers, and the energy retailer. The energy cooperatives goal is to maximize profit for its members.
Dairy farmers	Dairy farmers play an important role in this business ecosystem. They are producers of cow dung and consumers of digestate and organic fertilizer. The cow dung is an important input for the digestions process. Besides, the dairy industry is heavily regulated. Hence, regulation dictates the number of cows the farmers can have, the amount of cow dung that can be applied on the land as fertilizer, etc. The goal of the dairy farmers is to reduce CO2 and at the same time find cost efficient solutions for managing cow dung, fossil fertilisers, and fossil fuels. In other words, they want to reduce their carbon footprint and reduce farming costs.
Agriculture farmers	Agriculture farmers refers to farmers who grow crops. The agriculture industry is again heavily regulated. The agriculture farmers mainly supply biomass and are consumers of digestate and organic fertilizer.
Energy retailer	The energy retailer plays an important role in this ecosystem. They are responsible for retailing the energy that is produced in the cooperative back to the members of the cooperative. The energy retailer plays an important role in making this business ecosystem viable. The energy retailer in this case passes on the profits made from the energy retail business back to the cooperative. Such energy retailers already exist for example NLD. Exploring the business model of such energy retailers is beyond the scope of this report for more information see (D'Souza et al., 2015).
Transporter	The transporter in this business ecosystem takes care of the logistics, i.e., the transport of cow dung, biomass, etc. from the farms to the digester and back. Their main goal here is to make profit.

Service concept: This section describes the service concept. The goal here is not be exhaustive, but to highlight the key aspects of the envisioned service concept. The energy cooperative is the central actor. The energy cooperative is formed by a heterogeneous mix of dairy farmers and agriculture farmers. The energy cooperative is responsible for collecting manure and biomass from different sources and processing it in to biogas and digestate. The dairy farmers pay the energy cooperative to collect the manure and further process it. The digestate is then returned to the farmers land. The digestate is first applied on the dairy farmers land. Second, the remainder digestate is then applied on agriculture farm lands. Finally, the remaining digestate is further processed in to organic fertilizer. The organic fertilizer is again used bought by the both agriculture and dairy farmers as substitute for fossil fuel fertilizers. The biogas is first processed in to green fuels and used as a substitute for fossil fuels. The farmers use this fuel as a substitute for diesel to run their farm machinery such as tractors. Part of the gas is then converted to heat, electricity, and CO2 and sold to the agriculture farmers. The electricity, heat, and CO_2 is used by the agriculture farmers in their green houses. The remainder gas is then sold. The electricity is sold via the energy retailer. The energy retailer processes the sales and then returns the profits earned from electricity sale back to the energy cooperative.

The service described above is subject to several regulations and assumptions. The key regulations and assumptions are made explicit here. Firstly, the current manure regulation defines the maximum amount of that manure that can be produced applied on farming land. Similarly, the maximum amount of digestate that can be applied on farming land is defined. Second, current regulation also regulates the use of organic fertilizer. Farmers, cannot use more than certain amount of organic fertilizer on farming land[1]. However, for the sake of this business case we have assumed that the government would remove such restrictions.

Next, the inputs described in table 7.2 were used to calculate profitability for each of the stakeholders described in table 7.1.

[1] https://www.rijksoverheid.nl/onderwerpen/mest/maximale-hoeveelheid-mestproductie

Table 7.2. The main economic values used in the calculation of the NPV

Main economic values	Value	Unit	Source
Interest on loan and Required rate of return	2.5	%	[13]
Economic write off period	15	Years	
CAPEX Main installation	**Value**	**Unit**	**Source**
AD system	€ 2,903,856.81	€	[43]
AD system 25000 ton/a including storage of feedstocks and manure and a second digester	1,700,000.00	€	Johannes van der Veen, interview
Scrap value installation after 25 years	5%	%/CAPEX	[44]
OPEX	**Value**	**Unit**	**Source**
Operation and maintenance	5	% Investment/a	[43]
Tax on products	0	%/costs resource	[45]
Income tax	25	%/costs resource	[46]
Transport by truck	0.20	€/ton.km	[43]
Electricity from grid	0.14	€/kWh	[47]
Natural gas from grid[c]	0.59	€/Nm^3	[47]
Diesel fuel	1.00	€/l	[14]
INCOME GREEN GAS[b]	**Value**	**Unit**	**Source**
Green gas market price[c]	0.020	€/kWh	[4]
SDE Subsidization (12 years)	0.065	€/kWh	[4]
SDE extended (additional 12 years)	0.065	€/kWh	[4]
Correction fee SDE Subsidization (12 years)	0.017	€/kWh	[4]
Correction fee SDE extended(12 years)	0.017	€/kWh	[4]
INCOME GREEN ELECTRICITY CHP[b]	**Value**	**Unit**	**Source**
Green electricity market price	0.025	€/kWh	[4]
SDE Subsidy electricity WKK (12 years)	0.068	€/kWh	[4]
SDE extended electricity WKK (additional 12 years)	0.068	€/kWh	[4]
Correction fee SDE Subsidization (12 years)	0.035	€/kWh	[4]
Correction fee SDE extended(12 years)	0.035	€/kWh	[4]
INCOME GREEN ELECTRICITY HEAT[b]	**Value**	**Unit**	**Source**
Green electricity market price	0.025	€/kWh	[4]
SDE Subsidization electricity WKK (12 years)	0.065	€/kWh	[4]
SDE extended electricity WKK (additional 12 years)	0.065	€/kWh	[4]
Correction fee SDE Subsidization (12 years)	0.024	€/kWh	[4]
Correction fee SDE extended (12 years)	0.024	€/kWh	[4]
CAPEX improvements	Value	Unit	Source
Heat recovery digestate	25	€/kWth	
Heat recovery with heat pump system	200	€/kWth	
Insulation of the AD system	4000	€/% improvement	
Second digester / manure storage	90	€/m3 (storage capacity)	[14]
CHP unit	946.16	€/kWe	[48]
Digestate separation unit	1.45	€/(m3 digestate/a)	[40]
Digestate upgrading system (reversed osmosis)	30	€/(Mg/a capacity)	[41]
Fueling station (approx. 4-8 trucks, tractors per day)	75000	€/(20-40 GGE/day)[d]	[49]

[a] The Increase of electricity and gas price per year is assumed based on [50] as the marked is very volatile and the price dependents on many factors

[b] The subsidy is determined by the SDE subsidies minus the correction fee

[c] Based market price gas of 12.5 €/MWh. Groningen natural gas and green gas have a higher energy content of 35 MJ/Nm^3 or 9.7 kWh/Nm^3

[d] GGE/day = Gallons of Gasoline Equivalent per day

Table 7.3. The main values of the added technologies

Added technologies	Value	Unit	Source
Efficiency heat exchanger	90	%	
COP value heat pump	5		[51]
Energy requirement second digester	5	MJ/Mg(FM)	
Energy requirement separator[a]	4.68	MJ/Mg FM	[52]
Energy use reversed osmosis	35	MJ/Mg FM	[41]
Energy use filling station[b]	4.68	MJ/Nm^3	[39]

[a] Based on an electric separator [52]

[b] INTERMECH BBR/FBR/VIP CNG compressors 55-450 kW / 75-600 HP [39]

Table 7.4. Main values for production of fossil fertilizers replaced by upgraded digestate

Fertilizers replaced	Nitrogen as N	Phosphate as P_2O_5	Potassium as K_2O	Units	Source
Market price fossil fertilizer	0.85	0.73	0.49	€/kg	[14]
Market price Green fertilizer	0.60	0.51	0.26	€/kg	[53]
Required energy for production	75.90	27.9	12.9	MJ/kg	[15, 54]
Emission during production	12.60	2.22	2.30	kgCO2eq/kg	[15, 54]
Environmental impact during production	1.77	0.76	0.24	Pt/kg	[15, 54]

Table 7.5. Scenarios used within the sensitivity analysis of the more sustainable farming cooperation cases

Variable or SI-Indicators	Worst %	Ave %	Best %	Source
(P)EROI	57.18%	100.00%	149.02%	[3]
Emission	194.16%	100.00%	21.74%	[3]
Impact	207.00%	100.00%	25.51%	[3]
Total investment	120.00%	100.00%	80.00%	
Salvage value	0.00%	5.00%	10.00%	[14, 44]
Biogas production	57.18%	100.00%	149.02%	[3]
Interest	6.00%	5.00%	2.00%	
Taxation on internal use	21%	6%	0%	[45]
Discarding digestate	50.00%	0.00%	0.00%	
Fertilizer price	150.00%	100.00%	50.00%	
Maintenances	7.00%	5.00%	3.00%	

Table 7.6. Energy and fertilizer use average Dutch dairy and agricultural farm

	Dairy farm	Agricultural farm	Natural areas	Unit	Source
Total land use the Netherlands	956000	995756	?	ha	
Diesel use	130	238	-	l/ha.a	[14]
Electricity use	940[a]	549	-	kWh/ha.a	[14]
Natural gas use	32[a]	10	-	Nm3/ha.a	
Water use	80[a]	10	-	m^3/ha.a	[14]
Nitrate cap	265	170	?	kg/ha.a	[14]
Phosphate cap	95	65	?	kg/ha.a	[14]
Potassium cap	225	225	?	kg/ha.a	[55]

[a] Based on two cows per hectare of land producing 8500 kg of milk per year [14]

[b] Based on average agricultural farm of 40 ha [47] KWIN table page. 57

Fig. 7.2. Indicates the estimated amount of value each stakeholder will capture from this ecosystem. This is also considered as the worst-case scenario. From the figure all the stakeholders will be able to earn a profit except for the central actor, which is the energy cooperative.

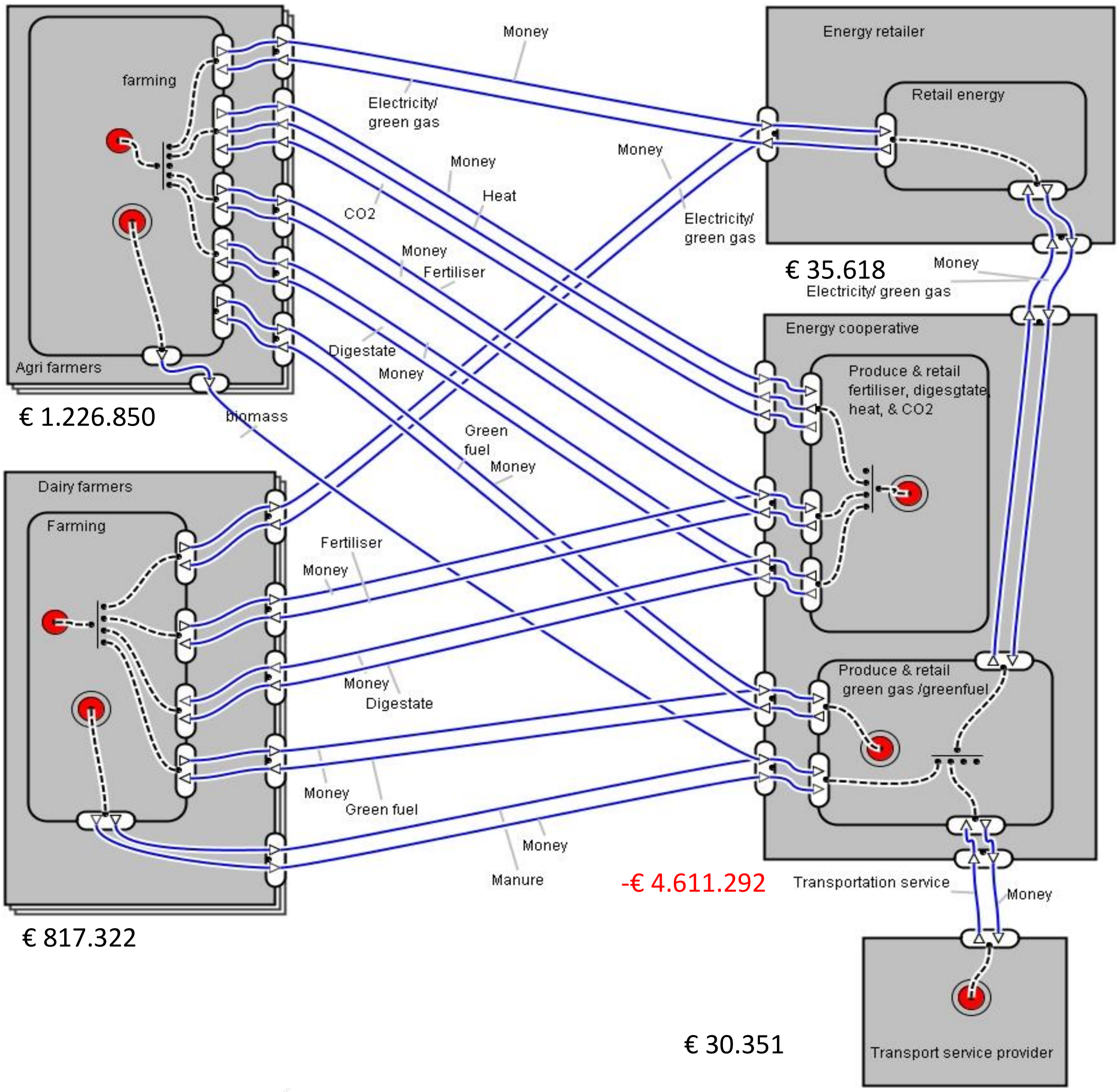


Fig. 7.2. The biogas ecosystem with NPV – worst case scenario

8. STEP 6: Feedback session on business case

The members of the cooperative profit much by participating in the energy cooperative. The losses incurred by the energy cooperative far exceed the combined profits earned by the other stakeholders. Therefore, this business ecosystem is unviable. This is largely because we have assumed the current manure regulations govern this business ecosystem. The current regulation restricts farmers from using organic fertilizer as a replacement for fossil fuel fertilizer. Besides, we have also assumed that the farmer will pay standard natural gas prices for both heat and CO_2 combined. If this business ecosystem is implemented today the worst-case scenario is also the most likely scenario.

Fig. 7.3. depicts the best-case scenario for the business ecosystem. Here we assume that the government allows farmers to use organic fertilizer as a replacement for fossil fuel fertilizer. Also, the farmers pay current natural gas prices for CO_2 and heat separately. Furthermore, the farmers make less profit from this whole ecosystem because they pay for the losses incurred by energy cooperative. They do that simply because the energy cooperative is a central actor. Without the central actor, it will be very difficult to realize and operate this business ecosystem. It is also important to note that the SDE subsidy and green fuel subsidy are vital to the viability of this business ecosystem.

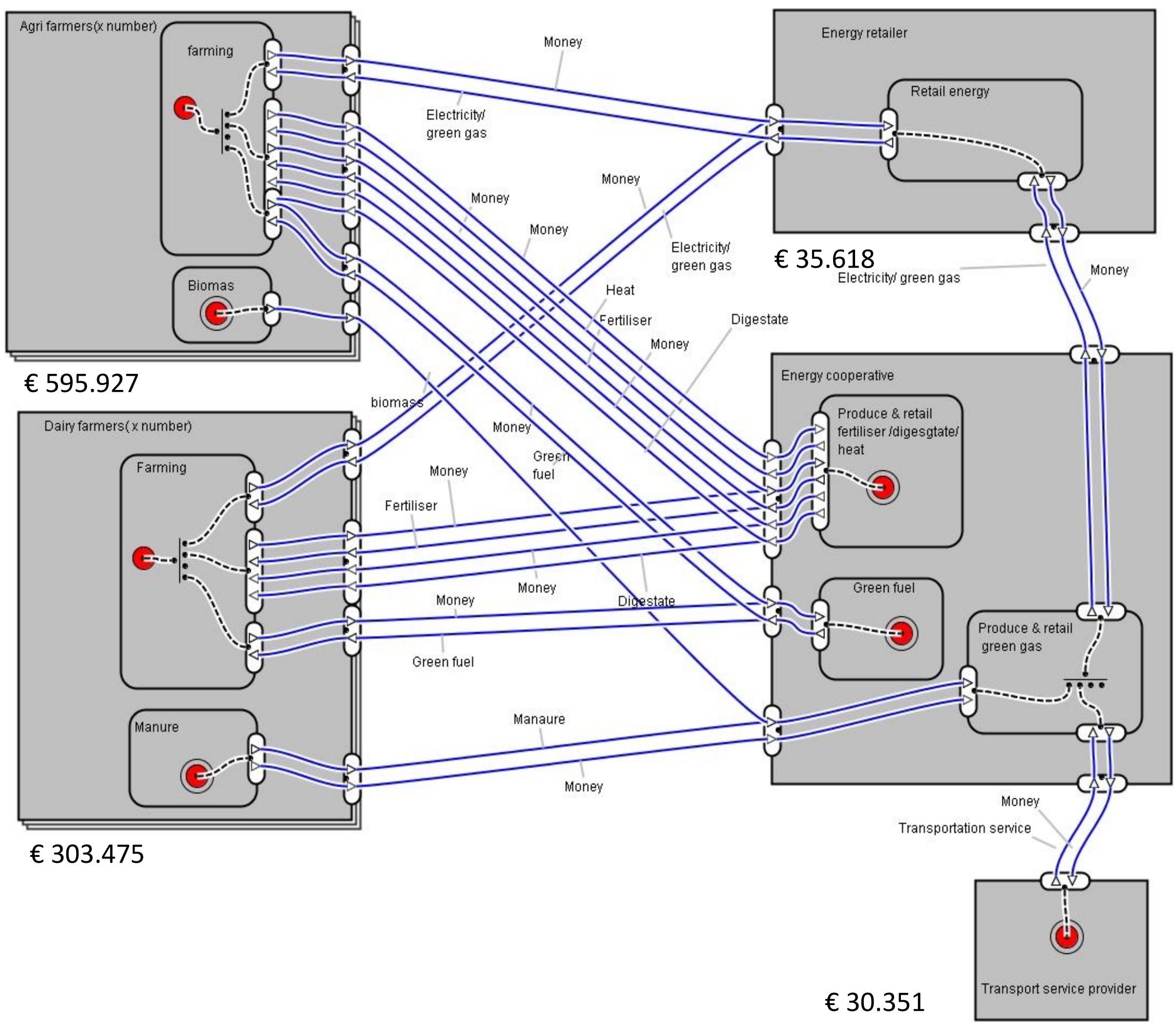


Fig. 7.3. The biogas ecosystem with NPV – Best case scenario

As mentioned previously, the viability of this business ecosystem largely depends on the government allowing the use of organic fertilizer as replacement for fossil fertilizer. If this happens the fossil fertilizer will suffer a great deal. Nevertheless, this will make farming far more sustainable it is than today.

9. DISCUSSION

Energy production through AD is a promising method for producing a renewable and flexible energy carrier. However, the production and utilization pathways are complex systems, containing multiple factors and variables which must be taken into account. The accuracy of the results presented in this report depends strongly on the quantity and quality of the data it contains, which comes from both literature and practice (table discussions with the farmers and interview companies). However, these sources still contain a wide range of data. Therefore, the models used for calculating the results were extensively validated before being implemented.

Using organic material in a biological process and uncertainties surrounding business cases inherently creates variations and sensitivities. The most sensitive values connected to biomass use within the project include the feedstocks, (e.g. biogas potential, methane potential, organic dry matter content, and environmental impacts of the collection and/or cultivation process). Within the economic variables, biogas production, maintenance, and interest are most dominant. However, high sensitivity often results as a combination of circumstances working with or against the process (e.g. bad harvest, high energy use harvest, low methane yields of crop, low market prices, and weak regulations). Furthermore, Specific biomass potentials are often difficult to quantify and differ by season and specific location.

The biomass potential is spread out evenly over the municipality for determining average transport distances. Transport distances are difficult to quantify and normalize; therefore, within this report average transport distances are used, although transport distances can differ significantly per specific location. The biomass described in this article could have other uses (e.g. stable flooring, animal feed) which must be considered (e.g. straw and harvest remains). Within this research, soil emissions from farming activities are not included, as well as impact on the quality of the soil when removing additional organic material or digesting manure and returning digestate to the fields. The use of green fertilizers replacing fossil fertilizers is currently not allowed by the European Union, there are however exceptions made within the Netherlands for some companies. Also, subsidy schemes for a cooperative AD system are currently not present within the Netherlands, therefore, the green gas subsidy scheme is chosen. Within the context aforementioned, clear regulations and subsidies are needed over longer periods of time to create the correct foundation for sustainable business cases for farm scale circular AD systems.

10. CONCLUSION

Applying the aforementioned circular symbiotic AD systems can lower the environmental impact of farming by decreasing dependency on fossil-based energy and fertilizers and lowering the carbon footprint from farming, helping the Dutch agricultural sector in achieving their stated environmental goals. Furthermore, a possible business case presents itself when adapting a cooperative system. Within this context, the use of digestate and upgraded digestate into green fertilizers is an important element for both environmental and economic cases. Replacing fossil fertilizers with green fertilizers has a substantial impact on all indicators of sustainability (e.g. EROI, GWP, Pt). Technically there are technologies available that can upgrade digestate into several types of green fertilizers. Of importance is the distribution of nutrients over the separated flows. Economically, green fertilizer production is expensive; however, if the correct prices are payed for the product it can bring the business case to a small positive gain.

Also of importance is the quality of the agricultural land and the quality of the feedstocks. The extraction of biomaterial from land per definition exhaust the soil, therefore a balance must be found between nutrients and organic material added to material removed. The removal of material is currently mostly as products or feed, however, taking the circular AD system into account an additional flow of organic (waste) material is needed as feedstock. The aforementioned will put additional strain on the soil balance and before using feedstocks there must be an understanding of the impact of utilization. In digesters many feedstock flows converge into one open system increasing the change of pollution and infection. If multiple farmers will make use of the cooperative AD system quality of the biomass input or feedstocks and biomass output or digestate must be guarded. Digesters could operate on thermophilic temperatures killing all harmful bacteria or feedstocks and digestate could be pasteurized using waste heat from the system itself.

Finally, cooperation between farmers is very important for a symbiotic system to be successful. Therefore, environmental, economic, and soil and feedstock quality have to be managed and controlled professionally. Additionally, the cooperation will need to have a strong and clear goal and objective to give it the strength of existence. All partners need to share, support, and stand behind the goals of the cooperation to make it successful.

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Appendix I: kitchen table discussions

Table AI-1. Vragenlijst Agro-Cycle project

Gegevens algemeen: vergadering	
Naam bedrijf	
Naam contactpersoon	
Type boerderij	Landbouw / Veehouderij

1) Gegevens locatie		
Gegevens landbouw	**Hoeveelheid**	**Opmerking**
Hoeveel land oppervlak heeft u totaal?		
Wat wordt er verbouwd?		
1)		
2)		
3)		
4)		
5)		
6)		
Hoeveel oppervlak wordt er effectief gebruikt per jaar?		
Waaruit bestaat het oppervlakte? (veen, weiden, grasland, bouwland, zand)		

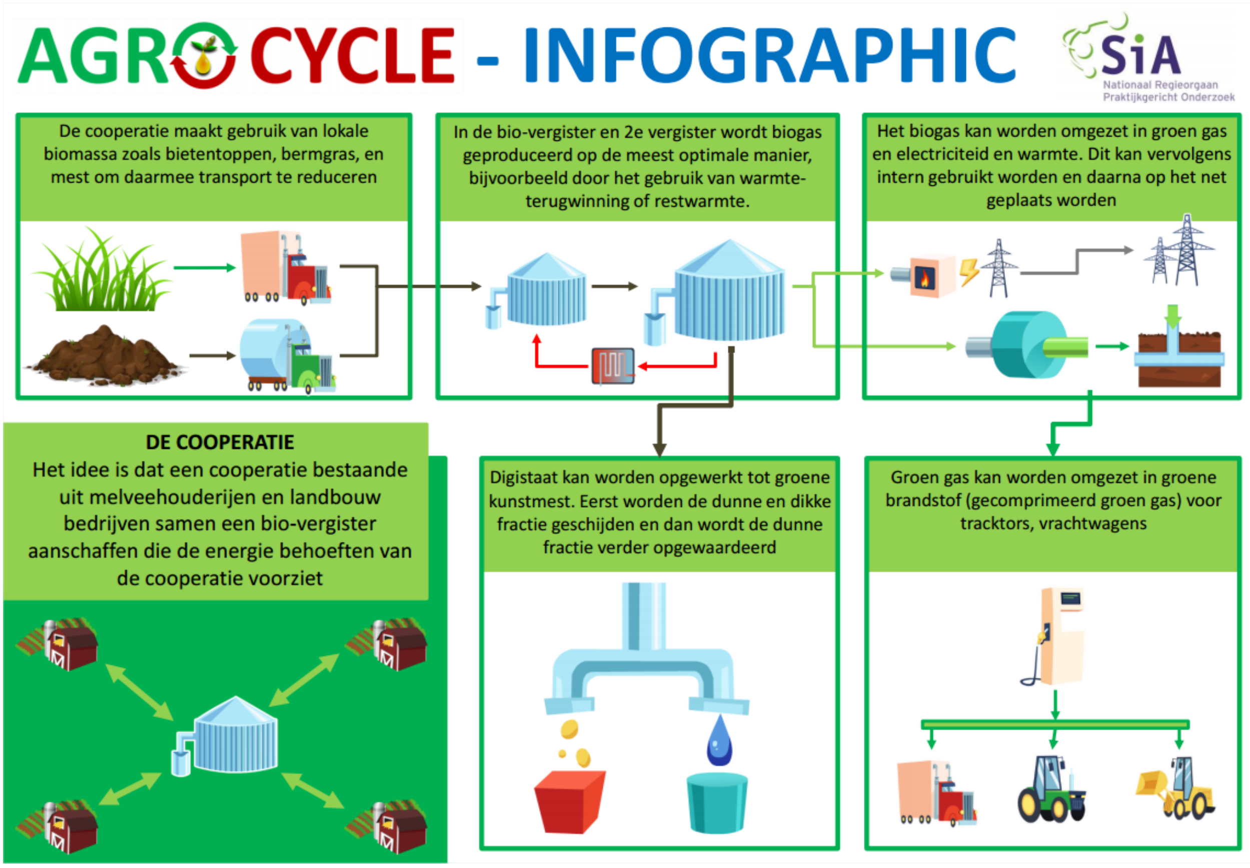
Gegevens veehouderij	**Hoeveelheid**	**Opmerking**
Hoeveel land oppervlak heeft u totaal?		
Wat voor vee?		
1)		
2)		
3)		
4)		
5)		
6)		
Hoeveel mest produceren uw vee?		
1)		
2)		
3)		
4)		
5)		
6)		

2) Energiegebruik				
Energiegebruik per energiedrager	**Hoeveelheid**	**Kosten per eenheid (kWh / m3)**	**Kosten totaal per jaar**	**Opmerking**
Elektriciteit				
Aardgas				
Diesel				
Anders?				
Produceert U ook duurzame energy?				
Soort energie	Jaarlijkse opbrengst	CAPEX Investeringskosten	OPEX onderhoudskosten per jaar	Opmerking
Zon PV				
Windturbine				
Vergister				
Of heeft U ook gedacht aan duurzame energy?				

3) Materiaalstromen op Uw bedrijf				
Wat voor soort bemesting gebruikt u? (organisch, organisch minerale, kunstmest, groene kunstmest, veemest)				
Bemesting	**Hoeveelheid**	CAPEX Investeringskosten	OPEX onderhoudskosten per jaar	**Waar komt de bemesting vandaan?**
1)				
2)				
3)				
4)				
5)				
6)				
7)				
8)				
9)				
10)				
Wat voor soort biomassa afvalstromen zijn er aanwezig op uw bedrijf?				
Afvalstroom	**Hoeveelheid**	**Kosten voor afhalen**	**Waar gaat de biomassa heen?**	**Opmerkingen**
1)				
2)				
3)				
4)				
5)				
6)				
7)				
8)				
9)				
10)				

4) Machine gebruik				
Wat voor machines bezit U	**Hoeveelheid**	**CAPEX Investering**	**OPEX Onderhoud**	**Opmerking**
1)				
2)				
3)				
4)				
5)				
6)				
7)				
8)				
9)				
10)				
Wat huurt u in van loonbedrijven	**Hoeveelheid**	**CAPEX Kosten inhuur**		**Opmerking**
1)				
2)				
3)				
4)				
5)				
6)				
7)				
8)				
9)				
10)				

Front



Back

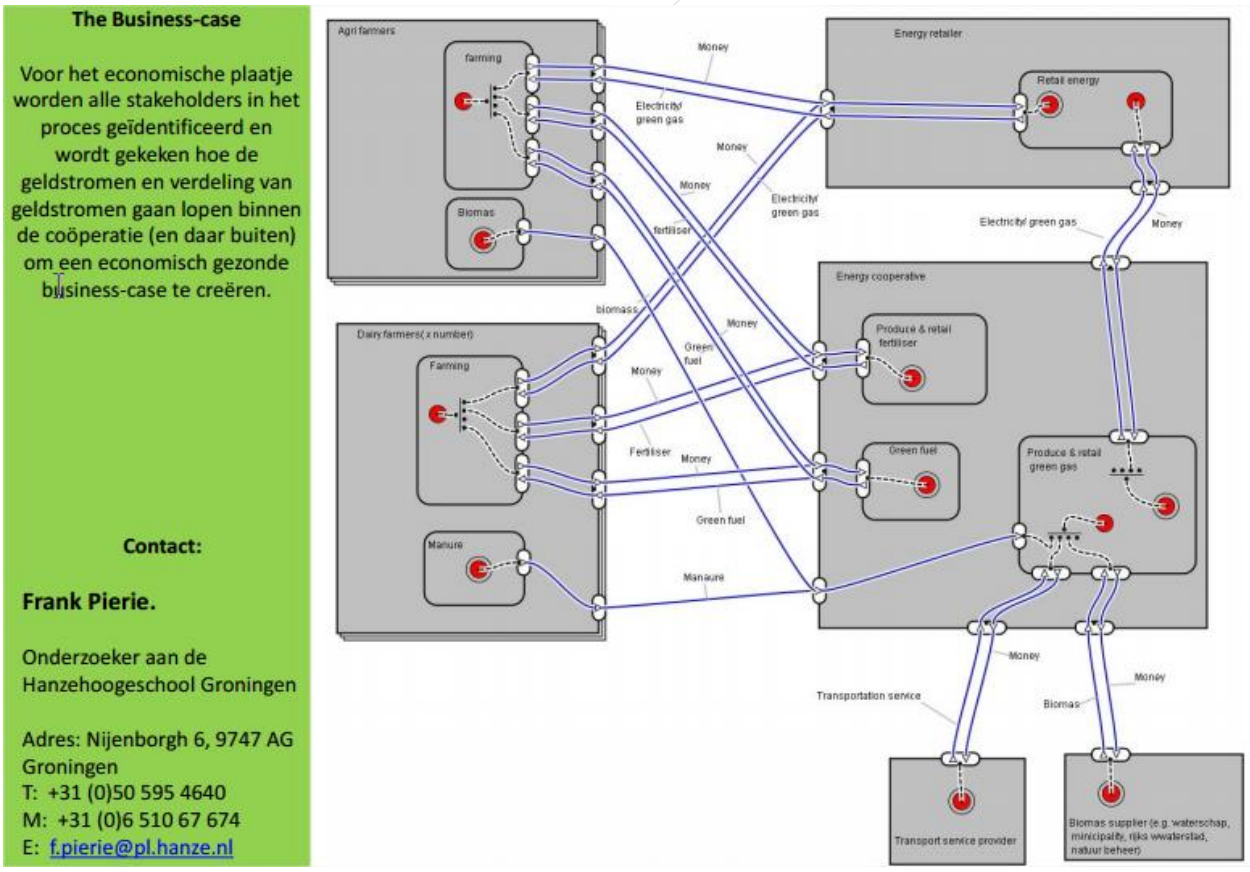


Fig. AI-1. Infographic used to explain Symbiotic AD system to farmers

Appendix II: Expressions of Planet used in this report

Efficiency expressed in (P)EROI: Before, during and sometimes after the exploitation of an energy source, input is needed in the shape of energy, installations, maintenance, transport, storage etc., which will impact the overall efficiency of the energy source. To indicate the energy efficiency of a process the (Process) Energy Returned on Invested factor, or (P)EROI, will be used. (P)EROI is defined as the ratio between the energy obtained from a resource to the energy expended in the production and processing of a resource (The factor is based on the EROI theory [56]). To determine the (P)EROI factor for a green gas production pathway, both the process energy invested and the energy returned must to be defined. The process energy invested includes; the direct energy needed to transform the raw materials to a final product (e.g. green gas injected into the gas grid); the indirect energy needed to produce the direct energy and raw materials; and the embodied energy of the constructions including maintenance. Energy returned is defined as the useful energy delivered, which could be in the form of biogas, green gas, electricity or heat. Additionally, the dependence on fossil fuels can be included in the factor, by indicating the fossil share of the energy invested. Overall, the (P)EROI factor can help to indicate the most efficient use of the green gas production pathway within a dynamic system. The (P)EROI will be expressed in a single factor. When the (P)EROI of a resource is greater than one it can be classified as a net energy producer, meaning that more energy is obtained from the resource than is expended in processing it. When the (P)EROI is equal or less than one the resource in question will become an energy sink or net energy consumer (e.g. storage system), meaning that less energy is obtained than is expended [56]. In theory the threshold between energy producer and energy sink is set at one, however in practice this point is often higher due to uncertainties (e.g. 1.5 up to 3, [57]).

Carbon footprint expressed in GWP 100: One of the main reasons for developing renewable resources is the reduction of fossil anthropogenic greenhouse gas emissions into the atmosphere. Every unit of fossil fuel consumed creates a net greenhouse gas increase potentially adding to global warming, destabilizing natural processes and endangering the Earth's carrying capacity for advanced forms of life [58-60]. However, there are many different types of greenhouse gasses present, all with their own greenhouse potentials and properties. To include most of them in a single score, the carbon footprint GWP100 scale is used [58]. The carbon footprint is expressed in carbon dioxide equivalents (CO_2eq) using the relevant 100-year global warming potential scale or GWP100, [58]. Within the approach the carbon footprint will be quantified as a net increase or decrease of GWP100. The biomass used in the green gas production pathway is assumed to be carbon neutral, as part of the organic carbon cycle, where carbon is trapped by photosynthesis and released through decomposition in a continuous cycle. The additional emissions originating from the cultivating and processing of the biomass are incorporated in the carbon footprint. There are two main net producers of GWP incorporated in the approach; first, carbon dioxide absorbed in biomass may be converted and emitted as a stronger greenhouse gas (e.g., methane), therefore increasing the overall GWP potential; second, use of fossil energy sources in the green gas production pathway will create anthropogenic emissions resulting in a net increase of GWP. The increase or decrease in GWP caused by the green gas production pathway is a simple and transparent ruler, making it comparable to other energy sources of fossil and renewable origin.

Environmental impact expressed EcoPoints: The overall impact on the environment will be expressed with the ReCiPe 2008 Eco indicator, used by the SimaPro model [61]. When following the ISO 14040 and 14044 generic frameworks, an LCA inventory usually results in a very long list of emissions, consumed resources and sometimes other items. The interpretation of this list is often complex and difficult to comprehend. The ReCiPe LCIA procedure method is designed to help with this interpretation through the use of the Eco indicator. "An indicator" is an overall expression of total load on the environment (as currently understood in science), based on the damage-oriented approach. The indicator uses weighting factors wherein damage is brought into perspective and is made comparable to other types of damage [62]. The following explanation is used for the ReCiPe 2008 indicator.

“ReCiPe uses an environmental mechanism as the basis for the modelling. An environmental mechanism can be seen as a series of effects that together can create a certain level of damage to for instance, human health or ecosystems. For instance, for climate change we know that a number of substances, increases the radiative forcing, this means heat is prevented from being radiated from the earth to space. As a result, more energy is trapped on earth, and temperature increases. As a result of this we can expect changes in habitats for living organisms, and as a result of this species may go extinct. In ReCiPe eighteen midpoint indicators are calculated, and three (more uncertain) endpoint indicators are calculated. The motivation to calculate the endpoint indicators, is that the large numbers of midpoint indicators are very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning. The indicators at the endpoint level are intended to facilitate easier interpretation, as there are only three, and they have a more understandable meaning [62].”

Overall, the three impact categories (human health, ecosystems, resource depletion) are brought together into a single score through the use of damage models and normalization. Hence, ReCiPe 2012 indicator method provides a representation of the total environmental load exerted on human health, the ecology of the planet and resource depletion.